Spring 2014

Effects Of Wheat Grain Moisture: Quality, Germination, And Relationship To Accumulated Growing Degree Days

Kirsten Thomas
Purdue University

Recommended Citation

Thomas, Kirsten, "Effects Of Wheat Grain Moisture: Quality, Germination, And Relationship To Accumulated Growing Degree Days" (2014). *Open Access Theses*. 271.
https://docs.lib.purdue.edu/open_access_theses/271

Graduate School ETD Form 9
(Revised 12/07)

PURDUE UNIVERSITY
GRADUATE SCHOOL
Thesis/Dissertation Acceptance

This is to certify that the thesis/dissertation prepared

By Kirsten Thomas

Entitled
EFFECTS OF WHEAT GRAIN MOISTURE: QUALITY, GERMINATION, AND RELATIONSHIP TO ACCUMULATED GROWING DEGREE DAYS

For the degree of Master of Science

Is approved by the final examining committee:

Shaun Casteel
Chair

Kiersten Wise

Jeffrey Volenec

To the best of my knowledge and as understood by the student in the *Research Integrity and Copyright Disclaimer (Graduate School Form 20)*, this thesis/dissertation adheres to the provisions of Purdue University's "Policy on Integrity in Research" and the use of copyrighted material.

Approved by Major Professor(s): Shaun Casteel

Approved by: Joseph Anderson 01/02/2014
Head of the Graduate Program Date

EFFECTS OF WHEAT GRAIN MOISTURE: QUALITY, GERMINATION, AND RELATIONSHIP TO ACCUMULATED GROWING DEGREE DAYS

A Thesis

Submitted to the Faculty

of

Purdue University

by

Kirsten Lee Thomas

In Partial Fulfillment of the

Requirements for the Degree

of

Master of Science

May 2014

Purdue University

West Lafayette, Indiana

ACKNOWLEDGEMENTS

I would like to thank Dr. Herbert Ohm and Dr. Shaun Casteel for their excellent scholastic guidance, overwhelming support, and positive attitudes throughout my M.S. studies. You have set excellent examples and inspired me to go the extra mile.

I am also grateful to Andrew Westfall, my fellow graduate students, and our undergraduate research assistants for their many hours spent helping with hand harvest and sample processing. I will always fondly recall the memories we created during our time spent working together. Without your support, this would not have been possible.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Figure **Page**

Figure **Page**

ABSTRACT

Thomas, Kirsten Lee. M.S., Purdue University, May 2014. Effects of Wheat Grain Moisture: Quality, Germination, and Relationship to Accumulated Growing Degree Days. Major Professor: Shaun Casteel.

Bread wheat (*Triticum aestivum* L.) is a cereal crop of global importance. As global demand increases, it is essential to increase the quality and efficiency of crop production. Harvesting wheat early provides an opportunity for increased grain quality, and it may also allow the grower to double-crop soybean (*Glycine max* L.) after wheat more effectively. Our objectives were to determine if harvesting grain early, at high moisture would, 1) increase milling and baking quality and 2) improve germination potential. As a result of these objectives, we will develop a model to predict dry-down of wheat. Five soft red and five soft white winter wheat cultivars were grown at West Lafayette, IN, over two years using a randomized complete block design. Grain was sampled by hand as drying progressed from approximately 40 to 10% moisture. Milling and baking quality of the samples was tested at the USDA-ARS Soft Wheat Quality Laboratory in Wooster, OH. Parameters tested included flour yield, whole grain hardness, whole grain protein, flour protein, softness equivalent, lactic acid solvent retention capacity (SRC), sucrose SRC, estimated cookie diameter, and modified milling, baking, and softness equivalent scores. Germination was evaluated by the Indiana Crop Improvement Association. Additionally, grain moisture loss was compared with growing degree days (GDD) accumulated from heading date to harvest date to discern the relationship between grain dry-down and thermal time.

Overall, harvesting grain early at high moisture maintained, if not increased, milling and baking quality. Flour yield, one of the most important quality parameters, did not change as a result grain moisture across the two years and the cultivars of both wheat types (means ranging 64.8 to 68.4). Protein quality, as measured by lactic acid SRC, was not detrimentally affected by grain moisture in either year in both wheat types. In general, grain at 22 to 24% moisture displayed favorable milling and baking quality for most parameters. Cultivar response differed only in one quality parameter with soft red wheat in 2013. The remaining effects of harvest grain moisture were consistent within wheat types and years. Germination was unaffected by high grain moisture at harvest except for soft red wheat in 2013, in which germination increased as grain moisture decreased. Both wheat types showed a strong linear decrease in grain moisture with accumulation of GDDs after heading, but differed between years due to opposing weather patterns. While the drought conditions in 2012 caused a grain moisture loss of 2.1% per 10 accumulated GDD, relatively cooler, wetter conditions in 2013 caused a grain moisture loss of 1.4% per 10 accumulated GDD. These findings are important to growers who may want to increase the quality of their wheat as well as predicting the time to harvest the wheat early in order to plant double-crop soybean.

CHAPTER 1. A REVIEW OF LITERATURE

1.1 Introduction

Wheat (*Triticum aestivum* L.) is a cereal crop of global importance. Wheat is the most widely consumed grain in the world (67 kg per person annually), and the third most-produced cereal crop (647.4 million metric tons) behind maize and rice (FAO, 2010). Wheat production steadily increased in recent years with more arable land area planted to it than any other crop. The United States (US), European Union, and Canada represent the world's largest exporters of wheat, while Asia and Africa are the largest importers (FAO, 2010). The genetic and agronomic adaptability of wheat make it an ideal crop for diverse geographical areas. This is especially true in cooler climates, where tropical and semitropical crops are not well adapted (Kumar et al., 2012). Wheat products are represented across many different food cultures worldwide due to its adaptability. Nearly all of the ways wheat is consumed by people involved grinding or fractioning the grain (Dziki and Laskowski, 2010), and thus, the quality of the wheat is critical for milling and baking.

In the US, wheat types grown include durum wheat (*Triticum durum*), hard red spring and winter wheat, soft red winter wheat, hard white spring and winter wheat, and soft white spring and winter wheat. Total wheat production in the US averaged 60.9 million metric tons from 2008 to 2012 (FAO, 2013). Products made from US wheat include a wide variety of pastas, breads, crackers, cakes, pastry products, and others. Though wheat is produced throughout the US, the majority is grown in the Great Plains region, from North Dakota to Texas (*Six Basic Classes of Wheat*, 2013). However, more land is being planted to spring wheat as breeding efforts to push wheat to more northern latitudes have led to the development of cultivars with more tolerance for these colder environments (FAO, 2010).

1.2 Classifications of Wheat

Wheat is classified based on several characteristics such as grain texture, grain color, and growth habit. These traits are a result of biological processes that have important implications to the physiology, management, and end-use of the grain. Grain color, texture, and growth habit are independent traits and can occur in all combinations

1.2.1 Grain Texture

The grain texture of wheat is divided into hard or soft (Souza et al., 2012). The key genes controlling grain texture, *Pina* and *Pinb*, are located on chromosome 5DS of the wheat genome (Carter et al., 2012). Allelic differences in these genes are responsible for the major phenotypic differences in grain texture (Carter et al., 2012). Different grain textures are necessary to produce a wide variety of wheat products. The softness or hardness of the grain is typically quantified by the measuring the starch amylose content (Carter et al., 2012), which is typically done using the Single Kernel Characterization System (SKCS) 4100 from Perten Instruments. This instrument measures kernel weight and size, crushing resistance, and kernel hardness. Lower SKCS values correspond to softer endosperm texture, and higher SKCS values correspond to harder endosperm texture (Carter et al., 2012).

Soft wheat has a soft endosperm and was typically high in starch (Souza et al., 2012). Soft wheat is produced in the eastern third of North America and high rainfall areas west of the Rocky Mountains (Souza et al., 2012). Soft wheat is primarily used for chemically (alkaline) leavened baked goods (e.g., cakes, cookies, and other confectionary products) (Finney, 1990). Generally, it had a smaller starch particle size, lower gluten strength, greater flour yield, and a smaller water retention capacity when compared to hard wheat (Finney, 1990).

The endosperm texture of soft wheat was primarily due to the presence of friabilin, a protein associated with the starch granule membrane (Souza et al., 2012). When friabilin binds to the starch granule, the particle size of the flour is reduced and the damage to starch produced by milling is reduced. This resulted in reduced flour water absorption. Increased endosperm softness usually increased flour recovery (Souza et al., 2012).

Hard wheat has a hard endosperm, as evidenced by high SKCS values (Carter et al., 2012). The majority of hard wheat is produced west of the Mississippi River in the dry, temperate climates. Yeast-leavened products (e.g., bread, pasta, noodles) are made from it (Souza et al, 2012). Hard wheat required more force to grind the grain to flour, which caused increased damage to the starch (Mason et al., 2007). This increased the amount of water the flour could absorb and the fermentation gas held by the resulting dough (Mason et al., 2007). The increased water absorption and particle size of hard wheat increased gluten cross-linking (Carter et al., 2012). This cross-linked protein network was the major cause of dough rise due to the carbon dioxide held by the network. Higher gluten strength also contributed to gluten cross-linking (Carter et al., 2012).

1.2.2 Grain Color

Grain color of wheat can be divided into two categories– white wheat and red wheat. White wheat is generally grown in drier areas (especially in the central and southern Great Plains region) of the US and is used for products desired to have a mild, sweet flavor, such as egg noodles and pastries (*Six Basic Classes of Wheat*, 2013). Red wheat is grown in different areas of the US depending on its type. Hard red wheat is generally grown west of the Mississippi River, across the Great Plains region from Canada to Mexico. Soft red wheat is grown throughout the US east of the Mississippi River. Red wheat is used for a variety of products, from cakes and crackers to bread and noodles (*Six Basic Classes of Wheat*, 2013) (end use is also largely dependent on grain texture; see section 1.2.1). Moist climatic conditions caused pre-harvest sprouting, especially in white genotypes (Groos et al., 2002). Genes for pre-harvest sprouting resistance seem to be tightly linked with the genes that control red coloring, though this has not been proven definitively (Groos et al., 2002).

1.2.3 Growth Habit: Winter vs. Spring Wheat

Vernalization requirement is the sensitivity of a crop is to early vegetative cold treatment (Kato et al., 2001), and it defines if wheat is winter or spring type. Snape et al. (2001) reported that genes controlling growth habit had pleiotropic effects, which had significant consequences for the adaptation of wheat to different environments. Vernalization was required by some cultivars to initiate spike formation, and the failure to fulfill the cultivar-appropriate vernalization requirement can result in reduced or no heading (Kosner and Pankova, 1998).

The growth habit of wheat is primarily under the control of genes influencing vernalization requirement, also known as "Vrn genes" (Kosner and Pankova, 1998). The Vrn genes are represented by three major genetic groups, Vrn1, Vrn2, and Vrn3. The Vrn1 genes, Vrn-A1, Vrn-B1, and Vrn-D1, are respectively located on chromosomes 5A, 5B, and 5D (Kato et al., 2001). Dominant forms of any of these genes, whether alone or in combination, conferred a spring growth habit, which makes the plant insensitive or only partially sensitive to vernalization. Spring wheat is typically planted and grown in regions that are too cold for winter wheat, where winterkill is a problem (Kato et al., 2001). These varying degrees of sensitivity to vernalization were due to the presence of multiple alleles for each of the Vrn genes. Conversely, winter wheat is completely recessive for these genes at all Vrn loci (Kato et al., 2001). These genes, both individually and in combination with one another, also imparted differing degrees of heading time in spring wheat (Kumar et al., 2012). Vrn-D1 is unique in that it is essential to all wheat plants, regardless of growth habit, because it was needed to establish floral meristem identity. However, in winter wheat, the gene remained repressed until adequate vernalization was received (Kumar et al., 2012). Spring wheat expressed Vrn-D1 constitutively due to the absence of the repressor binding site (Kumar et al., 2012). The frequency of the Vrn genes tends to vary with respect to region. Vrn3 becomes increasingly prevalent over Vrn1 and Vrn2 in areas closer to the equator (Stelmakh, 1998). The Vrn genes have close homology to similar genes in barley (*Hordeum vulgare* L.) and rice (*Oryza sativa*), which confirms their necessity via evolutionary conservation (Snape et al., 2001).

It is thought that genes controlling photoperiod and earliness per se genes (see section 1.6.1.1) also may influence growth habit. Both winter and spring wheat can be photoperiod sensitive or insensitive; growth habit did not directly correlate to photoperiodic response (Kato et al., 2001).

1.3 Milling and Baking Quality

A wide range of wheat flour characteristics is required to accommodate the varying demands of the food industry. In North America, it is generally desired to have a greater milling yield, and reduced flour water absorption and flour particle size. A variety of gluten strengths is required to manufacture a wide assortment of products, such as bread, noodles, cookies, and crackers (Souza et al., 2012). Consistency in quality is important for the highly-mechanized processing that grain undergoes post-harvest. In general, the growing environment currently has more control over most quality factors of wheat than the genetics, so improving the genetic stability of cultivars across environments is a major long-term goal in the wheat industry (Peterson et al., 1998). Laboratory analyses have been designed to evaluate quality more conveniently and less expensively than actually milling and baking products from the wheat flour. The USDA Soft Wheat Quality Laboratory recommends that soft wheat breeding programs focus on flour yield, sucrose solvent retention capacity (SRC), and softness equivalent, as these traits are highly heritable and easily measured on a large number of samples (Souza et al., 2012). Other traits significant to soft wheat quality research and selection for end-use are also described.

1.3.1 Test Weight

Test weight is the average weight of grain measured in pounds per bushel in the US, which was believed to be a good indicator of end-use quality (Kelman and Qualset, 1993). It is now known that test weight has little effect on most measures of milling and baking quality in wheat (Kelman and Qualset, 1993). In reality, the only significant effect of high test weight on milling and baking quality was a reduction in flour yield (Souza et al., 2012). High test weight was desirable to most grain traders because it is an indicator of the general density and soundness of the grain, and it was a factor of significant consideration for most grain buyers (Mason et al., 2007).

1.3.2 Flour Yield

Flour yield, also known as milling yield, is defined as the percent by weight of starch that is extracted from the whole grain (McKendry et al., 2001). It is considered a highly heritable trait and an excellent parameter for breeders to improve the quality of cultivars. It is also arguably the most commercially important trait as a high flour yield is desired by all end users of wheat. As little as a 1% increase in flour yield is considered a significant improvement in quality (McKendry et al., 2001). Wheat that is greater than 67.5% flour is desirable (Redinbaugh et al., 2013). Flour yield is negatively correlated with protein concentration and the SRC tests (Carter et al., 2012). The milling quality score is a composite of flour yield and softness equivalent (McKendry et al., 2001), making this trait an extremely important predictor of overall milling quality.

1.3.3 Softness Equivalent

Softness equivalent is a measure of the hardness of the endosperm in the wheat kernel. It is defined as the percent of particles that pass through a 471 μm mesh screen but stay above a 181 μm mesh screen after milling (Redinbaugh et al., 2013). It is highly heritable. A high softness equivalent contributes to the palatability of cakes, cookies, and other confectionary products. It is also one of the most commercially important milling and baking quality parameters. Half of the modified baking quality composite score is determined by the softness equivalent (McKendry et al., 2001), which is useful in rating overall baking quality of wheat. Soft wheat with 53 to 64% softness equivalent is desirable (Redinbaugh et al., 2013).

1.3.4 Solvent Retention Capacity (SRC)

The solvent retention capacity (SRC) tests predict commercial baking performance in several ways. Solvent retention capacity tests are considered highly heritable characteristics and are reliable for use in breeding programs (Carter et al., 2012; Guttieri et al., 2001). All SRC tests are very interrelated with positive correlations (Carter et al., 2012). Solvent retention capacity is determined by the ratio of various solvents retained by the flour after centrifugation to original sample weight, including the added solvents (Souza et al., 2012). The percent weight change after centrifuging the samples is the SRC value for each solvent (Gaines, 2004). This can also be expressed fractionally as the grams of solvent retained per kilogram of sample flour (Guttieri and Souza, 2003). The tests used a mixture of sample flour and a test-specific solution to evaluate lactic acid SRC, sucrose SRC, flour water absorption, and starch damage.

1.3.4.1 Lactic Acid SRC

Lactic Acid SRC essentially measures the strength of the gluten in the flour (Souza et al., 2012). In this test, a 5% lactic acid solution is mixed with the sample flour to assess gluten quality (Carter et al., 2012). Preferred values are above 87% (Redinbaugh et al., 2013). These values indicate the percentage of weight increase after flour is centrifuged with each solvent (Gaines, 2004). Stronger gluten flour will be used to produce bread and similar products, whereas weaker gluten flours will be used for soft-textured confectionary products. Lactic acid SRC is negatively correlated with cookie diameter. Soft wheat with strong gluten wheat may have poor pastry making quality, but can be used to create high-quality products such as crackers and flat breads (Gaines, 2004).

1.3.4.2 Sucrose SRC

Sucrose SRC evaluates arabinoxylan content by mixing 50% sucrose solution with the sample flour (Carter et al., 2012). Arabinoxylan is a nonstarch polysaccharide that is a main constituent of dietary fiber and can be major source of variation in flour water absorption (Souza et al., 2012). Increased arabinoxylan caused dough to have a thicker, stiffer consistency. This was desirable for breadmaking, but was undesirable for soft wheat products such as cookies and cakes (Courtin and Delcour, 2002). Target values are below 89% for soft wheat products, such as cookies, cakes, and crackers (Redinbaugh et al., 2013). Sucrose SRC is positively correlated with cookie diameter and negatively correlated with softness equivalent and flour yield.

1.3.4.3 Flour Water Absorption

Water is mixed with the sample flour to evaluate the overall ability of the flour to absorb water (Carter et al., 2012). The desired level of flour water absorption was low (less than 55%) for soft wheat and higher (greater than 62%) for hard wheat (Finney, 1990). Flour water absorption can be considered a measure of the “stickiness” of the resulting dough. Lower flour water absorption scores were correlated with less sticky dough, which was good for soft wheat products such as cakes, cookies, and crackers.

1.3.4.4 Starch Damage

The starch damage test estimates the amount of starch granules that will be damaged after the initial milling step. A 5% $NaCO_3$ solution was mixed with the sample flour (Carter et al., 2012). A 71% change in weight was the maximum acceptable level for quality baked goods, and lower values are preferred. Greater levels of starch damage are highly correlated with increased kernel hardness (Campbell et al., 2001).

1.3.5 Flour Protein Concentration

Flour protein is the percent by weight of the flour that is protein, as determined by NIR spectroscopy. An increased level of protein in wheat flour strengthens dough products and contributes to the entrapment of carbon dioxide gas produced during fermentation. It is generally accepted that heritability of protein content is low (Carter et al., 2012), but O'Brien and Ronalds (1987) estimated moderate heritability (16% to 50%). These values, coupled with the importance of this parameter to the end user, make it a characteristic worth consideration in breeding programs. Good quality bread making (hard) wheat typically has a flour protein concentration between 10.5% and 13.5%. A low level of flour protein (less than 10%) is desirable for soft wheat (Redinbaugh et al., 2013). Low protein flour is used for softer products, such as cakes, cookies and crackers; it can also be blended with very high (14% or above) protein flour for bread making (Mason et al., 2007). It is negatively correlated with grain yield (Carter et al., 2012) and flour extraction (Otteson et al., 2008).

1.3.6 Cookie Diameter

Cookie diameter describes the final diameter of a test cookie after baking. During baking, cookie dough spreads until the viscosity of the dough is great enough to counter the gravitational force that causes the dough to increase in diameter (Abboud et al., 1985). Cookie diameter is an indication of flour texture, water absorption, protein strength, and starch characteristics. Together, these give a general prediction of the overall pastry baking quality of flour (Gaines, 2004). It was negatively correlated with water absorption, sucrose SRC, and protein concentration and was positively correlated with milling score (Carter et al., 2012). A larger cookie diameter (18.1 to 19.5 cm) is desired for soft wheat, as this produces better confectionary products (Redinbaugh et al., 2013).

1.4 Factors Affecting Milling and Baking Quality

Both genetic and environmental factors have been shown to affect milling and baking quality characteristics (Baenziger et al., 1985). The overall trend in soft wheat has been small, incremental improvements in milling yield and a steady reduction in flour protein concentration (Souza et al., 2012). Despite the steady improvement in milling yield, it has been hypothesized that more than half of the genes affecting end-use quality have not yet been defined (Li et al., 2011). Agronomic practices that increase milling and baking quality have not been well studied, but will likely become increasingly important.

1.4.1 Genetic Factors

Both native variation in the wheat genome and genes introgressed from related species have improved the quality of wheat. Since wheat is marketed on its end-use characteristics, it is essential that breeders continue to increase their understanding of the genetic controls behind quality traits (Carter et al., 2012). Quantitative trait loci (QTLs) have been correlated to milling and baking quality traits on 20 of the 21 chromosomes in wheat (Souza et al., 2012). Linkage groups contributing to milling and baking quality traits have been mapped to every wheat chromosome except 7D (Campbell et al., 2001).

1.4.1.1 Native Wheat Genes Affecting Quality

Chromosomes 3B and 4D have been found to contain several linkage groups affecting milling quality. Chromosome 3B contains 10 QTLs within a 26.2 cM region, and chromosome 4B contains 7 QTLs within an 18.8 cM region (Carter et al., 2012). Starch composition was controlled by three major genes, called granule bound starch synthase genes (GBSS), which were located on chromosomes 4A, 7A, and 7D (Carter et al., 2012). The *Pinb* gene controlling kernel texture was also a major QTL for cookie baking traits, hydration, and milling quality (Carter et al., 2012). Additive allelic effects of the *Glu-A1, Glu-D1, and Glu-B1* loci improved the flour protein content by increasing high molecular weight glutenin. These genes have also been shown to have significant interaction effects with salinity and nitrogen levels (see section 1.4.2.7) (Kelman and Qualset, 1993).

1.4.1.2 Genes Introgressed From Other Crops

Chromosomal translocations 1BL.1RS and 1AL.1RS from rye (*Secale cereale*) are widely used to improve disease resistance, increase yield, and expand adaptability of wheat. However, these introgressions negatively influenced the milling and baking quality of hard and soft wheat (McKendry et al., 2001). The translocation1AL.1RS was more detrimental to quality than 1BL.1RS (McKendry et al., 2001).

In hard wheat, both translocations were limited because the resulting dough was too sticky, had poor strength, and was intolerant to over-mixing. Flour yield, softness, or milling quality were not affected in the hard wheat backgrounds (McKendry et al., 2001). In soft wheat, both translocations considerably reduced softness equivalent and increased alkaline water retention capacity.

Genetic background has been shown to affect quality traits more strongly than the translocations. If the translocation was placed into a high-quality background, the background may compensate for the negative effects of the translocation on quality (McKendry et al., 2001). The use of translocations was a viable option for some cultivars while still reaping other agronomic benefits from the translocation.

Most current breeding efforts, especially in the US, utilize a very narrow gene pool of cultivars that excludes valuable genetic variation found in wild relatives and landraces. This was largely due to the linkage drag these species impart (McKendry et al., 2001). The use of introgression lines were used to mitigate this issue and was pioneered in several other crops, such as soybean (*Glycine max*) (Concibido et al., 2003), rice (*Oryza sativa*) (Tian et al., 2006), tomato (*Solanum lycopersicum*) (Almeida et al., 2011), and barley (*Hordeum vulgare*) (March et al., 2012), and could be a promising approach in wheat as well.

Limited research has been done using introgression lines derived from synthetic wheat to discover QTL that contribute to improved end use quality. Using this approach, Li et al. (2011) found 116 pleiotropic QTLs with positive effects for bread-making quality that were detected on chromosomes 2D, 3A, 4A, 4B, 5A, and 6A. Importantly, these QTLs were shown to have little to no negative effect on grain yield. However, the positive effects of these QTLs need to be confirmed using direct tests for milling and baking quality to further assess their usefulness.

1.4.2 Environmental Factors

In addition to the influence of genetic background on milling and baking quality characteristics, the environment plays a tremendous role in growth and development of high quality grain. Several environmental factors that have been shown to affect milling and baking quality are examined below.

1.4.2.1 Seeding Rate

Limited studies have shown seeding rate to have mixed effects on milling and baking quality characteristics. Geleta et al. (2002) found that decreased seeding rates (16 kg ha^{-1} and 33 kg ha^{-1}) decreased flour yield and increased flour protein when compared to standard seeding rates (65 kg ha^{-1}). Otteson et al. (2008) found no influence of seeding rate on quality characteristics. Higher seeding rate (4.2 million seeds ha^{-1}) reduced spike size and the number of tiller spikes (Otteson et al., 2008), which could cause a reduction in overall yield. Higher rates should be approached with caution, as this may not be economical in a production setting.

1.4.2.2 Nitrogen

It was well documented that fertile soil improved overall crop health and produced good grain yield. The roles of the essential nutrients in plants are many, but it is nitrogen (N) that has the most significant impact on milling and baking quality. While genotype was the key factor in determining grain protein levels, N fertilization and environmental conditions caused variation within cultivars grown across several environments (Souza et al, 2004). Generally, increasing the rate of applied N increased grain protein content over all wheat genotypes when conditions supported crop growth (Kimball et al., 2001; Souza et al., 2004). Increasing rates of N also increased the Hagberg falling number (see section 1.7.3) (Ayoub et al., 1994). Results for N timing and treatment type have been mixed. Otteson et al. (2008) found little influence of N timing on grain protein between a single application (granular urea, applied and incorporated 100% at preplant), two-way split (50% dry granular urea at preplant and 50% foliar urea ammonium nitrate (UAN) solution at five-leaf stage), and three-way split (33% dry granular urea at preplant, 33% foliar UAN at five-leaf stage, and 33% foliar UAN post-anthesis). However, Ayoub et al. (1994) reported splitting the N application (granular ammonium nitrate, broadcast and incorporated by hand, 60% at seeding and 40% at anthesis) increased grain protein. Increasing N rates increased grain protein under irrigated conditions, but caused little change when moisture was limited (Souza et al., 2004). Over-fertilization of N on soft wheat would be detrimental to quality since the target is low protein compared to hard wheat with high protein targets (Otteson et al, 2008; Souza et al, 2004).

1.4.2.3 Available Water

As global precipitation patterns change and water scarcity becomes an issue of increasing importance, the effects of moisture on wheat milling and baking quality has been an area of intense interest. Drought stress, particularly during grain fill, decreased starch deposition in the grain while protein deposition increased (Jenner et al., 1991). Low total rainfall during the growing season was correlated with high protein concentration even when cultivars and N management strategies were selected to produce low-protein grain (Souza et al., 2004). Gooding et al. (2003) reported similar results and found grain protein to be most severely increased by drought stress in the fourteen day period following anthesis under controlled conditions. Xu and Yu (2006) studied the effect of total water (via drip irrigation, 60 mm received at key growth stages from sowing to yellowing) available throughout the growing season on grain protein content. Protein concentration increased under moderate drought stress, but decreased under more severe drought (Xu and Yu, 2006). However, the extent of the changes in these parameters strongly depended on the cultivar x environment interaction (Guttieri et al., 2000).

The effect of water stress on flour yield was less discernible. Jenner et al. (1991) reported an overall decrease in starch as a result of drought conditions during grain fill. However, Guttieri et al. (2000) reported only some cultivars had reduced flour yield as a result of severe moisture stress, while other cultivars remained largely unaffected. Reduced flour yields of some cultivars may be a reflection of the genetic sensitivity to water stress in general, as flour yield was largely dependent on genotype (Souza et al., 2004).

After physiological maturity, excess rain can cause pre-harvest sprouting in some cultivars (see section 1.7.3). Flour milled from sprouted kernels exhibits a darker color, greater cookie spread, and higher protein content (due to hormonal signals that increase protein synthesis) than that made from sound kernels. These effects decreased the quality of soft wheat (Lorenz and Valvano, 1981).

1.4.2.4 Temperature

While the effects of temperature on crop plants has long been a topic of interest, globally changing climate patterns have brought this issue to the forefront of research.

Though it is widely believed that heat stress has negative effects on grain protein, several studies have shown that heat stress has variable effects on this quality (Peterson et al., 1998). Corbellini et al. (1997) extensively studied the effects of high temperature on wheat quality over two years. Two cultivars of durum wheat and two cultivars of bread wheat were grown in a greenhouse with ample water and temperature (35-40^{0}C) treatments imposed after anthesis. Early heat shock did not alter the protein, but late heat shock (with longer exposure) reduced protein content and reduced dough strength (Corbellini et al., 1997). Plants that were allowed to acclimate to the increase in temperature appeared to acquire thermotolerance, as reductions in protein content were less pronounced (Corbellini et al., 1997). Flour yield was not affected by high temperature (Corbellini et al., 1997).

However, these results may not be applicable to all genotypes. In a study of 75 hard winter and durum wheat (*Triticum durum*) cultivars, Stone and Nicolas (1995) found end-use quality varied considerably among genotypes when plants were held at 40^{0}C for three days. Bhullar and Jenner (1985) reported that temperatures over 30^{0}C during grain fill may increase grain protein, but small differences were evident between hard winter wheat cultivars. Gooding et al. (2002) also found an increase in grain protein when plants were exposed to elevated temperature (28^{0}C) at all stages after anthesis. This effect was increased as water was limited (Gooding et al., 2002).

Peterson et al. (1998) studied the effect of high temperature (above 32^{0}C) in a field environment over 30 hard red winter wheat cultivars grown in 17 locations over 2 years. Brief exposure to high temperature increased overall baking quality, but over 90 hr of accumulated exposure to 32^{0}C reduced overall baking quality (Peterson et al., 1998).

Differences in response between cultivars and locations were apparent; however, the overall trend in heat stress response was the same (Peterson et al., 1998). From these studies, it is evident that the overall effect of temperature on milling and baking quality is difficult to quantify and depends strongly on the cultivar x environment interaction.

1.4.2.5 Atmospheric CO_2

With the advent of climate change, the predicted change in atmospheric CO_2 concentration has become a concern of increasing importance to production agriculture. Kimball et al (2001) found that elevated CO_2 had negligible effects on milling and baking quality under ample water and N regimes. However, elevated CO_2 decreased yield during of drought stress and low soil N levels when compared with these stresses alone (Kimball et al., 2001). Sufficient supply of water and N should help preserve the quality and productivity of wheat as CO_2 increases.

1.4.2.6 Disease Pressure

In general, diseases caused shriveling of the wheat kernel and thus reduced flour yield (Everts et al., 2001). Several wheat diseases common in the Eastern Corn Belt impact milling and baking quality in other ways.

Fusarium head blight or scab (caused by *Fusarium graminearum*) severely reduces quality in wheat and is arguably the disease that most significantly impacts milling and baking quality. This is primarily due to the accumulation of mycotoxins, principally deoxynialenol (DON), in the grain following fungal infection. Even low levels of DON in wheat are considered unacceptable by both grain buyers and end users. Severely infected grain has extremely low test weight, chalky texture, and can become so shriveled as to be ejected with the chaff during combine harvest (Shaner, 2007). It also exhibits reduced milling yield (Kolb, 2007).

Shriveled grain and low test weight are common problems in fields infected by rusts and blotches, as these diseases severely affect the plant during the grain filling period. Leaf rust (caused by *Puccinia triticina*) was shown to decrease the softness equivalent score when it occured early in the growing season (Everts et al., 2001). Leaf blotch (caused by *Septoria tritici* and *Stagonospora nodorum*) tended to decrease SRC values, flour yield, and test weight (Everts et al., 2001).

Conversely, powdery mildew (caused by *Blumeria graminis*) affected the crop earlier in the season by decreasing or completely inhibiting tiller development, which severely limits grain yield (Shaner, 2007). Everts et al. (2001) reported seed treatment [triadimenol (Baytan 30F, Gustafson, Plano,TX) at a rate of 0.26 g a.i. kg^{-1} of seed] to control powdery mildew was effective, but decreased softness equivalent. Reduced softness equivalent is undesirable for soft wheat.

The effects of viral infection on specific quality parameters are somewhat limited, but it is generally accepted that viruses decreased the milling and baking quality. Wheat spindle streak mosaic virus (*Bymovirus*) reduced flour yield and baking quality score and increased protein content of susceptible soft wheat cultivars (Cunfer et al., 1988). Barley yellow dwarf virus (*Luteovirus*) (Fitzgerald and Stoner, 1967), wheat soilborne mosaic virus (*Furovirus*) (Finney and Still, 1963), and wheat streak mosaic virus (*Potyvirus*) (Finney and Still, 1963) showed similar effects. Curiously, Triticum mosaic virus (*Potyvirus*) did not affect milling or baking qualities of hard wheat (Miller et al., 2012).

1.4.2.7 Salinity

In certain regions of the Western US, particularly California, disposal of salinized water from the irrigation of other crops is a subject of intense interest. It has been shown that certain cultivars of wheat can tolerate the intense salinity of this water, thereby making the use of the water for irrigation of wheat a viable option for maximizing its use (Kelman and Qualset, 1993). However, it is important to consider the effect the intense saline conditions may have on the quality of the wheat.

Salinity has been found to decrease overall grain yield, test weight, and water absorption. Conversely, flour yield and milling score increased (Kelman and Qualset, 1993). These data suggest that soft wheat genotypes known for excellent quality will likely maintain their quality when grown in saline conditions. (Kelman and Qualset, 1993).

1.4.2.8 Organic Management

As consumer demand for organic food products increases, the effects of organic management on milling and baking quality have become a subject of interest. One study on Canadian hard red spring wheat revealed significant management x cultivar effects on baking qualities. Interestingly, this research found no evidence that older cultivars (developed before the advent of synthetic fertilizers and chemicals) performed more favorably under organic management (Mason et al., 2007). The study found test weight and gluten strength to be higher under conventional management, but found no differences in protein content (Mason et al., 2007). However, these characteristics met the grading requirements in both management systems, suggesting that organic systems do not hinder wheat grown for good bread making quality. Further, the significant cultivar x management system interaction suggests that some cultivars could be developed specifically for organic management in future breeding efforts (Mason et al., 2007).

1.5 Wheat Maturity

Wheat maturity is an extremely important characteristic for placement in a given production area. Different measures of maturity are used throughout the scientific and production communities. Physiological maturity can be defined as the peak dry weight of the seed. Harvest maturity is the grain moisture level at which the seed can be harvested and safely stored. The temporal difference between these two can be very difficult to predict due to their strong dependence on environment (May and VanSanford, 1992). Anthesis and heading dates are often used to predict time to physiological maturity, but this is also difficult, as this time frame was a function of the kernel growth rate (May and VanSanford, 1992).

Early-maturing varieties are useful in avoiding both abiotic (e.g., drought, hail) and biotic stresses (e.g., pathogens, insects) that affect quality. Also, early-maturing wheat cultivars increase the possibility of an early harvest, which could allow growers the option to double-crop in regions with short growing seasons. Many studies indicate that the numerous possible combinations of vernalization (Vrn) genes, photoperiod sensitivity (Ppd) genes, and earliness per se genes lend significant phenological flexibility to wheat worldwide. This will be especially useful in the future, as climate change becomes an increasing concern in production agriculture (Kumar et al., 2012).

1.6 Factors Affecting Maturity

Most of the factors controlling maturity in wheat (once dormancy has been broken in response to environmental changes, if applicable) are genetic. Heading time was an extremely important measure of earliness in wheat, as it determined, to a great extent, how adaptable a given line was to a given environment (Kato et al., 2001). Earliness was especially important in areas where mid- and late-season water stresses were limiting to yield (Zare-kohan and Heidari, 2012).

1.6.1 Genetic Factors

The growth and development of wheat is controlled primarily by three groups of genes. These include genes controlling vernalization requirement (Vrn genes), those controlling photoperiodic reaction (Ppd genes), and earliness per se genes (Kosner and Pankova, 1998). Studies show that all three groups have pleiotropic effects, which have significant consequences for the adaptation of wheat to different environments (Snape et al., 2001). These genes as well as their interactions with the environment control the total period of vegetative growth and time to anthesis (Stelmakh, 1998). In combination, the Vrn genes were responsible for approximately 70 to 75% of the variation in heading date, while Ppd genes and earliness per se genes encompassed about 20% and 5%, respectively (Stelmakh, 1998).

1.6.1.1 Vrn Genes

In addition to the previously mentioned functions of the Vrn genes (see section 1.2.3), these genes have additional effects on earliness. The Vrn-D1 gene confers reduced vernalization requirement and shorter narrow-sense earliness. Additionally, cultivars with this gene headed earlier in some studies (Kato et al., 2001; Snape et al., 2001). Both heading date and vernalization requirement have been shown to be stable across environments (Kato et al., 2001).

1.6.1.2 Ppd Genes

In wheat, photoperiod sensitivity is controlled by three major genes, Ppd1, Ppd2, and Ppd3, which are respectively located on chromosomes 2D, 2B, and 2A. Dominant forms of these genes conferred varying degrees of photoperiod insensitivity (Kato et al., 2001). Photoperiod insensitive plants flowered earlier under short days (less than 12 hours daylight) than photoperiod sensitive varieties (Kumar et al., 2012). Cultivated wheat was generally a long-day (greater than 12 hours daylight) plant (Kato et al., 2001).

Ppd3 conferred the highest degree of insensitivity to photoperiod. Ppd1 displayed partial photoinsensitivity, largely in the later stages of development, while Ppd2 conferred partial insensitivity primarily during the early stages of development (Stelmakh, 1998). Some studies showed that dominant Ppd genes, particularly Ppd1 and Ppd3, could shorten the duration of the vernalization requirement (Kosner and Ponkova, 1998; Stelmakh, 1998). A semidominant mutation, Ppd-D1a, has been shown to confer rapid flowering (photoperiod insensitivity) under both short and long day conditions. This mutation interacted with the dominant Vrn-1 genes to cause extremely early flowering, especially under higher temperatures. This gene was a major source of earliness in wheat germplasm globally (Kumar et al., 2012).

1.6.1.3 Earliness per se Genes

Narrow-sense earliness, also known as earliness per se, was defined by Kato and Wada (1999) as, “the earliness of fully vernalized plants grown under long-day conditions.” Though this trait was controlled by many minor polygenes, it has been shown to be highly heritable (Kato and Wada, 1999). Earliness per se genes controlled varietal earliness independent of environmental conditions, which was in strong contrast to the Vrn and Ppd genes (Zare-kohan and Heidari, 2012). Little is known about this class of genes; however, it was hypothesized that earliness per se genes play a key role in early maturity. More research is needed to fully understand the effects of these genes on wheat physiology.

1.6.2 Environmental Factors

Day length, light intensity, and precipitation have major impacts on wheat after heading and cause variation in the time period between heading and physiological maturity. Specific effects varied with the cultivar and intensity of these environmental factors. Heading date was not always correlated with harvest maturity (May and VanSanford, 1992). In an experiment by VanSanford (1985), several cultivars of soft red winter wheat reached physiological maturity at the same time, despite their one-week spread in heading date (VanSanford, 1985). This was also consistent with the findings of more recent experiments (May and VanSanford, 1992).

1.7 Effects of Harvest and Post-Harvest Management on Quality

Several aspects of near-harvest management (e.g., timing, method, drying, storage) can affect the milling and baking qualities of wheat. Proper handling and management during this stage of production will ensure optimum wheat quality.

1.7.1 Harvest Grain Moisture

Mangels and Stoa (1928) observed no differences in baking quality for hard wheat harvested at various stages of maturity (“dough, hard dough, glazed, normal ripe, and dead ripe”). A study of grain moisture effects on soft wheat quality by Yamazaki (1976) also found no differences in quality of grain harvested at various moisture levels. Scott et al. (1957) found that yield, test weight, and kernel weight of hard red winter wheat were optimized as grain was harvested near 40% moisture under field conditions but harvested by hand. Protein content was also highest at 40% moisture (Scott et al., 1957). However, only three cultivars were tested in only one location at Hays, Kansas, across two years, and the latter year was excluded from statistical analysis due to drought conditions and poor stands (Scott et al., 1957). A study of hard red spring wheat by Tipples (1980) reported that protein content was minimized at 50% grain moisture but improved as grain moisture decreased. This study was performed over 4 years and one to four cultivars (depending on the year) in Manitoba, Canada (Tipples, 1980). Since protein was highly influenced by cultivar, fertility, and environment (Souza et al., 2004), variation between these two studies was expected. Tipples (1980) also observed increased flour yield and decreased starch damage and water absorption as grain moisture decreased. Kirleis et al. (1982) studied one cultivar of soft red winter wheat over two years at Lafayette, Indiana. The percentage of broken kernels was minimized when grain moisture was 27% or less before mechanical harvest. Milling rating (MR=flour yield-flour ash x 100%) increased as grain moisture decreased. Flour yield and cookie diameter were not affected by grain moisture. These results suggest that preferred milling and baking quality was achieved when grain moisture was less than 27% (Kirleis et al., 1982).

1.7.2 Drying Temperature

Ramser (1954) studied flour yield and cookie diameter in two cultivars of soft wheat harvested at approximately 20% grain moisture. Drying temperatures of 54^{0}C,

60^0C, 71^0C, 82^0C, and 93^0C did not significantly affect either quality characteristics. However, Finney et al. (1962) studied the effect of drying temperature on quality on one cultivar of hard red winter wheat harvested between 27.0% and 12.4% moisture in one year at Hays, Kansas. Drying temperatures above 71^0C decreased the overall bread-baking quality for grain that was harvested at various moisture levels with the more damage to grain with more moisture (Finney et al., 1962). Wheat harvested at very high moisture (38% or above), demonstrated severely reduced milling quality when grain was dried above 66^0C. Drying wheat at lower temperature (38^0C) preserved its quality much more effectively (Kirleis et al., 1982).

1.7.3 Preharvest Sprouting

Preharvest sprouting (PHS) occurs when excess humidity or rainfall cause the seed to germinate when it is still in the grain head. This trait was associated with reduced milling and baking quality as well as agronomic difficulties (Humphreys and Noll, 2002). When sprouting occurs, large amounts of α-amylase were released into the kernel, which decreased its water holding capacity (Mason et al., 2007). Ground particle size was smaller when seeds had sprouted prior to harvest, but the energy requirement for grinding was less. Preharvest sprouting reduced the kernel hardness and caused the flour to darken in color, which was undesirable for milling and baking end-users. Bread dough made from sprouted wheat tended to be too sticky, which caused handling problems and made the end product more difficult to slice (Dziki and Laskowski, 2010).

This trait was strongly dependent on genotype. Many cultivars of white wheat were susceptible to PHS while most cultivars of red wheat were resistant. Selecting lines that reach physiological maturity earlier than usual was currently the easiest way to avoid

PHS. Efforts to breed new cultivars of white wheat that are PHS resistant have been only marginally successful.

Preharvest sprouting is quantified using the Hagberg falling number. “Falling number” refers to the amount of time (in seconds) it takes for the Hagberg steel ball to fall through a flour-water slurry, which was heated to release the starch from the flour. If sprouting has occurred, enzymes have actively broken down some of the starch. The absence of the starch makes the slurry less viscous and causes the ball to fall faster (Sorenson, 2006). Low falling numbers are indicative of poor milling and baking quality. Grain graded with a low falling number is difficult to export as a commodity, which is a problem in countries like the US, where wheat is a major export (Humphreys and Noll, 2002). According to Mason et al. (2007), falling numbers exceeding 400 seconds were related to a starch with little α-amylase activity and little to no PHS.

1.8 Effects of Harvest Moisture on the Viability of Seed Wheat

Early harvest at high grain moisture has been shown to have a positive effect on seed germination time of three hard red winter wheat cultivars (Scott et al., 1957). Kidd and West (1919) reported that storage life was longer for more mature seed. Scott et al. (1957) confirmed this finding and also reported that more mature seed had better seedling vigor.

1.9 Effects of Weather on Wheat Dry Down

In wheat, effects of climatic conditions during the vegetative and grain fill periods have been studied at length, but effects of these conditions after the grain has reached physiological maturity has not. In corn (*Zea mays*), dry-down rates after physiological maturity were estimated by using growing degree days (GDDs) (Cavalieri and Smith, 1985). Growers could predict the readiness of the crop as it relates to current conditions and the weather forecasted in the days to come, and thus, make informed decisions for optimizing harvest. These predictions in wheat would be very useful, especially as growers consider double-cropping soybean.

1.10 Objective of Research

Previous studies have shown mixed results for the effects of harvest grain moisture on milling and baking quality of wheat. While some reported no differences (Mangels and Stoa, 1928; Yamazaki, 1976), others showed harvest grain moisture significantly affected grain quality (Tipples, 1980; Kirleis et al., 1982). Since all of these studies used a relatively small number of cultivars, more research over a greater number of genotypes could improve predictability. The milling and baking responses of modern cultivars have not been thoroughly investigated with respect to harvest grain moisture. Our objectives were to determine the effects of harvest grain moisture (i.e., harvest timing) on the milling and the baking quality of wheat. We hypothesized that harvesting wheat early (at higher grain moisture levels) would increase the milling and baking quality of the grain. Additional objectives were to determine the effects of grain moisture on the germination potential of wheat and to develop a model to predict dry-down of wheat. We hypothesized that harvesting wheat early (at higher grain moisture levels) would improve germination due to less exposure to environmental fluctuations (e.g., temperature, rainfall). According to previous dry-down models of corn, we hypothesized that best relationship for wheat predictions would be based on GDD. This would open opportunities for growers to produce higher quality wheat, while increasing the likelihood that soybean could be double-cropped following wheat.

1.11 References

Abboud, A.M., R.C. Hoseney, and G.L. Rubenthaler. (1985). Factors Affecting Cookie Flour Quality. Cereal Chemistry 62(2):130-133.

Almeida, J., L. Quadrana, R. Asis, N. Setta, F. de Godoy, L. Bermudez, S.N. Otaiza, J.V. Correa da Silva, A.R. Fernie, F. Carrari, and M. Rossi. (2011). Genetic dissection of vitamin E biosynthesis in tomato. Journal of Experimental Botany 62(11):3781-3798.

Ayoub, S., S. Guertin, J. Fregeau-Reid, and D.L. Smith. (1994). Nitrogen Fertilizer Effect on Breadmaking Quality of Hard Red Spring Wheat in Eastern Canada. Crop Science 34:1346-1352.

Baenziger, P.S., R.L. Clements, M.S. McIntosh, W.T. Yamazaki, T.M. Starling, D.J. Sammons, and J.W. Johnson. (1985). Effect of Cultivar, Environment, and Their Interaction and Stability Analyses on Milling and Baking Quality of Soft Red Winter Wheat. Crop Science 25:5-8.

Bhullar, S.S. and C.F. Jenner. (1985). Differential Responses to High Temperatures of Starch and Nitrogen Accumulation in the Grain of Four Cultivars of Wheat. Australian Journal of Plant Physiology 12:363-375.

Campbell, K.G., P.L. Finney, C.J. Bergman, D.J. Gualberto, J.A. Anderson, M.J. Giroux, D. Siritunga, J. Zhu, F. Gendre, C. Roue, A. Verel, and M.E. Sorrells. (2001). Quantitative Train Loci Associated with Milling and Baking Quality in a Soft x Hard Wheat Cross. Crop Science 41:1275-1285.

Carter, A.H., K.G. Campbell, C.F. Morris, and K.K. Kidwell. (2012). Chromosomes 3B and 4D are associated with several milling and baking quality traits in a soft white spring wheat (*Triticum aestivum* L.) population. Theoretical and Applied Genetics 124:1079-1096.

Cavalieri, A.J., and O.S. Smith. (1985). Grain Filling and Field Drying of a Set of Maize Hybrids Released From 1930 to 1982. Crop Science 25(5):856-860.

Concibido, V.C., B. La Vallee, P. McLaird, N. Pineda, J. Meyer, L. Hummel, J.Yang, K. Wu, X. Delannay. (2003). Introgression of a quantitative trait locus for yield from *Glycine soja* into commercial soybean cultivars. Theoretical and Applied Genetics 106:575-582.

Corbellini, M., M.G. Canevar, L. Mazza, M. Ciafffi, D. Lafiandra, and B. Borghi. (1997). Effect of the Duration and Intensity of Heat Shock During Grain Filling on Dry Matter and Protein Accumulation, Technological Quality, and Protein Composition in Bread and Durum Wheat. Australian Journal of Plant Physiology 24:245-260.

Courtin, C.M. and J.A. Delcour. (2002). Arabinoxylans and Endoxylanases in Wheat Flour Bread-making. Journal of Cereal Science 35:225-243.

Cunfer, B. M., J.W. Demski, and D.C. Bays. (1988). Reduction in Plant Development, Yield, and Grain Quality Associated with Wheat Spindle Streak Mosaic Virus. Phytopathology 78:198-204.

Dziki, D. and J. Laskowski. (2010). Study to analyze the influence of sprouting of the wheat grain on the grinding process. Journal of Food Engineering 96:562-567.

Everts, K. L., S. Leath, and P.L. Finney. (2001). Impact of Powdery Mildew and Leaf Rust on Milling and Baking Quality of Soft Red Winter Wheat. Plant Disease 85:423-429.

Finney, K.F., M.D. Shogren, R.C. Hoseney, L.C. Bolte, and E.G. Heyne. (1962). Chemical, Physical, and Baking Properties of Preripe Wheat Dried at Varying Temperatures. Agronomy Journal 54:244-247.

Finney, K.F. and W.H. Still. (1963). Effects of two viruses on milling and baking properties of wheat grain and flour and on probable nutritive value of forage wheat. Agronomy Journal 55:476-478.

Finney, P.L. (1990). Flour, milling, and end-use quality of Ohio wheat. p.78-87. In J.E. Beuerlein (ed.) Profitable wheat management. Ohio State University Extension Bulletin 811.

Fitzgerald, P.J. and W.N. Stoner. (1967). Barley Yellow Dwarf in Wheat (*Triticum aestivum* L.). I. Yield and Quality of Hard Red Winter Wheat Infected With Barley Yellow Dwarf Virus. Crop Science 7:337-341.

Food and Agriculture Organization. Food Outlook, May, 2008. Accessed online. <http://www.foa.org/docrep/010/ai466e/ai466e03.htm>.

Food and Agriculture Organization. FAOSTAT: Wheat Production in the United States 2008-2012, August 2013. Accessed online. <http://faostat.fao.org/site/567/DesktopDefault.aspx?PageID=567#ancor>.

Gaines, C.S. (2004). Prediction of Sugar-Snap Cookies Diameter Using Sucrose Solvent Retention Capacity, Milling Softness, and Flour Protein Content. Cereal Chemistry 81(4):549-552.

Geleta, B., M. Atak, P.S. Baenziger, L.A. Nelson, D.D. Baltenesperger, K.M. Eskridge, M.J. Shipman, and D.R. Shelton. (2002). Seeding Rate and Genotype Effect on Agronomic Performance and End-Use Quality of Winter Wheat. Crop Science 42:827-832.

Gooding, M.J., R.H. Ellis, P.R. Shewry, and J.D. Schofield. (2003). Effects of Restricted Water Availability and Increased Temperature on the Grain Filling, Drying, and Quality of Winter Wheat. Journal of Cereal Science 37:295-309.

Groos, C., G. Gay, M.R. Perretant, L. Gervais, M. Bernard, F. Dedryver, and G. Charmet. (2002). Study of the relationship between pre-harvest sprouting and grain color by quantitative trait loci analysis in a white x red grain bread-wheat cross. Theoretical and Applied Genetics 104:39-47.

Guttieri, M.J. and E. Souza. (2003). Sources of Variation in the Solvent Retention Capacity Test of Wheat Flour. Crop Science 43:1628-1633.

Guttieri, M.J., R. Ahmad, J.C. Stark, and E. Souza. (2000). End-Use Quality of Six Hard Red Spring Wheat Cultivars at Different Irrigation Levels. Crop Science 40:631-635.

Guttieri, M.J., D. Bowenb, D. Gannonc, K. O'Brien, and E. Souza. (2001). Solvent Retention Capacities of Irrigated Soft White Spring Wheat. Crop Science 41(4):1054-1061.

Humphreys, D.G. and J. Noll. (2002). Methods for characterization of preharvest sprouting resistance in a wheat breeding program. Euphytica 126:61-65.

Jenner, C.F., T.D. Ugalde, and D. Aspinall. (1991). The Physiology of Starch and Protein Deposition in the Endosperm of Wheat. Australian Journal of Plant Physiology 18:211-226.

Kato, H., S. Taketa, T. Ban, N. Iriki, and K. Murai. (2001). The influence of a spring habit gene, *Vrn-D1*, on heading time in wheat. Plant Breeding 120:115-120.

Kato, K., and T. Wada. (1999). Genetic analysis and selection experiment for narrow-sense earliness in wheat by using segregating hybrid progenies. Breeding Science 49:233-238.

Kelman, W.M. and C.O. Qualset. (1993). Responses of Recombinant Inbred Lines of Wheat to Saline Irrigation: Milling and Baking Qualities. Crop Science 33:1223-1228.

Kidd, F. and C. West. (1919). Physiological pre-determination: The influence of the physiological condition of the seed upon the course of subsequent growth and upon the yield. III. Annals of Applied Biology 5:157-170.

Kimball, B.A., C.F. Morris, P.J. Pinter Jr., G.W. Wall, D.J. Hunsaker, F.J. Adamsen, R.L. LaMorte, S.W. Leavitt, T.L. Thompson, A.D. Matthias, and T.J. Brooks. (2001). Elevated CO_2, drought and soil nitrogen effects on wheat grain quality. New Physiologist 150:295-303.

Kirleis, A.W., T.L. Housley, A.M. Emam, F.L. Patterson, and M.R. Okos. (1982). Effect of Preripe Harvest and Artificial Drying on the Milling and Baking Quality of Soft Red Winter Wheat. Crop Science 22:871-876.

Kolb, F.L. (2007). Development of Fusarium Head Blight-Resistant Wheat Varieties. Illinios Crop Protection Technology Conference. Conference proceedings:53-56. Univ. of Illinios, Urbana-Champaign, Illinois. Accessed online. <http://ipm.illinois.edu/education/proceedings/icptcp2007.pdf>.

Kosner, J. and K. Pankova. (1998). The detection of allelic variants at the recessive *vrn* loci of winter wheat. Euphytica 101:9-16.

Kumar, S., V. Sharma, S. Chaudhary, A. Tyagi, P. Mishra, A. Priyadarshini, and A. Singh. (2012). Genetics of flowering time in bread wheat *Triticum aestivum*: complementary interaction between vernalization-insensitive and photoperiod-insensitive mutations imparts very early flowering habit to spring wheat. Journal of Genetics 91(1):33-47.

Li, Y., R. Zhou, J. Wang, X. Liao, G. Branlard, and J. Jia. (2011). Novel and favorable QTL allele clusters for end-use quality revealed by introgression lines derived from synthetic wheat. Molecular Breeding 29:627-643.

Lorenz, K. and R. Valvano. (1981). Functional Characteristics of Sprout-Damaged Soft White Wheat Flours. Journal of Food Science 46:1018-1020.

Mangels, C.E. and T.E. Stoa. (1928). Effect of stage of maturity on composition and baking quality of Marquis wheat. Cereal Chemistry 5:385-394.

March, T. J., D. Richter, T. Colby, A. Harzen, J. Schmidt, and K. Pillen. (2012). Identification of proteins associated with malting quality in a subset of wild barley introgression lines. Proteomics 12:2843–2851.

Mason, H, A. Navabi, B. Frick, J. Donovan, D. Niziol, and D. Spaner. (2007). Does growing Canadian Western Hard Red Spring wheat under organic management alter its breadmaking quality? Renewable Agriculture and Food Systems 22(3):157-167.

May, L. and D.A. VanSanford. (1992). Selection for Early Heading and Correlated Response in Maturity of Soft Red Winter Wheat. Crop Science 32:47-51.

McKendry, A. L., D.N. Tague, and K. Ross. (2001). Comparative Effects of 1BL.1RS and 1AL.1RS on Soft Red Winter Wheat Milling and Baking Quality. Crop Science 41:712-720.

Miller, R. A., T.J. Martin, and D.L. Seifers. (2012). Impact of Triticum mosaic virus infection hard winter wheat milling and bread baking quality. Journal of Science, Food, and Agriculture 92:772-775.

O'Brien, L. and J.A. Ronalds. (1987). Heritabilities of small-scale and standard measures of wheat quality for early generation selection. Journal of Agricultural Research 38:801-808.

Otteson, B.N., M. Mergoum, and J.K. Ransom. (2008). Seeding Rate and Nitrogen Management on Milling and Baking Quality of Hard Red Spring Wheat Genotypes. Crop Science 48:749-755.

Peterson, C.J., R.A. Graybosch, D.R. Shelton, and P.S. Baenziger. (1998). Baking quality of hard winter wheat: response of cultivars to environment in the Great Plains. Euphytica 100:157-162.

Ramser, J.H. (1954). Effects of drying temperature on quality of wheat. Ill. Agric. Exp. Stn. Circ. 730.

Scott, G.E., E.G. Heyne, and K.F. Finney. (1957). Development of the Hard Red Winter Wheat Kernel in Relation to Yield, Test Weight, Kernel Weight, Moisture Content, and Milling and Baking Quality. Agronomy Journal 49(9):509-513.

Shaner, G. (2007). Wheat Disease Management. Illinios Crop Protection Technology Conference. Conference proceedings:51-52. Univ. of Illinios, Urbana-Champaign, Illinois. <http://ipm.illinois.edu/education/proceedings/icptcp2007.pdf>.

Six Basic Classes of Wheat. (2013). Minnesota Association of Wheat Growers. Accessed online. <http://www.smallgrains.org/WHFACTS/6classwh.htm>.

Snape, J.W., R. Sarma, S.A. Quarrie, L. Fish, G. Galiba, and J. Sutka. (2001). Mapping genes for flowering time and frost tolerance in cereals using precise genetic stocks. Euphytica 120:309-315.

Sorenson, B. (2006). Falling Numbers 101: Determining Sprout Damage in Grain. Prairie Grains Magazine, Issue 76. March 2006. Accessed online. <http://www.smallgrains.org/springwh/Mar06/falling/falling.html>.

Souza, E.J., C. Sneller, M.J. Guttieri, A. Sturbaum, C. Griffey, M. Sorrells, H. Ohm, and D. VanSanford. (2012). Basis for Selecting Soft Wheat for End-Use Quality. Crop Science 52:21-31.

Souza, E.J., J.M. Martin, M.J. Guttieri, K.M. O'Brien, D.K. Habernicht, S.P. Lanning, R. McLean, G.R. Carlson, and L.E. Talbert. (2004). Influence of Genotype, Environment, and Nitrogen Management on Spring Wheat Quality. Crop Science 44:425-432.

Stelmakh, A.F. (1998). Genetic systems regulating flowering response in wheat. Euphytica 100:359-369.

Stone, P.J. and M.E. Nicolas. (1995). A survey of the effects of high temperature during grain filling on yield and quality of 75 wheat cultivars. Australian Journal of Plant Physiology 46:475-492.

Tian, F., D.J. Li, Q. Fu, Z.F. Zhu, Y.C. Fu, X.K. Wang, and C.Q. Sun. (2006). Construction of introgression lines carrying wild rice (*Oryza rufipogon* Griff.) segments in cultivated rice (*Oryza sativa* L.) background and characterization of introgressed segments associated with yield-related traits. Theoretical and Applied Genetics 112:570-580.

Tipples, K.H. (1980). Effect of immaturity on the milling and baking quality of red spring wheat. Canadian Journal of Plant Science 60:357-369.

VanSanford, D.A. (1985). Variation in kernel growth characters among soft red winter wheats. Crop Science 25:626-630.

Xu, Z.Z. and Z.W. Yu. (2006). Nitrogen metabolism in flag leaf and grain of wheat in response to irrigation regimes. Journal of Plant Nutrition and Soil Science 169:118-126.

Yamazaki, W.T. (1976). Soft Wheat Quality of Preripe Harvested Wheat. Crop Science 16:572-574.

Zare-kohan, M. and B. Heidari. (2012). Estimation of Genetic Parameters for Maturity and Grain Yield in Diallel Crosses of Five Wheat Cultivars Using Two Different Models. Journal of Agricultural Science 4(8):74-85.

CHAPTER 2. EFFECTS OF HARVEST GRAIN MOISTURE ON MILLING AND BAKING QUALITY OF WHEAT

2.1 Abstract

Bread wheat (*Triticum aestivum* L.) is a cereal crop of global importance. Nearly all of the ways wheat is used involves grinding or fractioning the grain in some way. Thus, the milling and baking qualities of wheat are immensely important to producers, manufacturers, and end-users of food-grade wheat. In this study, we evaluated the effects of harvest grain moisture on eleven milling and baking quality parameters. We hypothesized that harvesting grain early, at high moisture, would increase milling and baking quality. Five soft red and five soft white winter wheat cultivars were grown at West Lafayette, IN, over two years. Grain was sampled by hand as drying progressed from 40 to 10% moisture. Samples were tested at the USDA-ARS Soft Wheat Quality Laboratory in Wooster, OH. Parameters tested included flour yield, whole grain hardness, whole grain protein, flour protein, softness equivalent, lactic acid solvent retention capacity (SRC), sucrose SRC, estimated cookie diameter, and modified milling, baking, and softness equivalent scores. Flour yield, one of the most important quality parameters, did not change as a result of grain moisture across the two years and the cultivars of both wheat types (means ranging 64.8 to 68.4%). Protein quality, as measured by lactic acid SRC, was not detrimentally affected by grain moisture in either year in both wheat types. Other parameters showed mixed results over years and wheat types. In most cases,

quality increased or remained unchanged when grain moisture was high. In general, grain harvested at 22 to 24% moisture displayed favorable milling and baking quality for most parameters. This finding is important to growers who may want to increase the quality of their wheat as well as harvest early to increase the possibility of double-cropping soybean (*Glycine max* L.) after wheat.

2.2 Introduction

The North American food industry requires wheat (*Triticum aestivum* L.) with a wide range of milling and baking characteristics to accommodate the manufacture of various food products. It is generally desired to have a greater flour yield with reduced flour water absorption and flour particle size. A variety of gluten strengths is required to manufacture a wide assortment of products, such as bread, noodles, cookies, and crackers (Souza et al., 2012). Consistency in quality is important for the highly-mechanized processing that grain undergoes post-harvest.

Though several types of wheat are grown across the United States, soft red (SR) wheat and soft white (SW) wheat are typically grown in the eastern Corn Belt. Soft grain types are well-suited to commercial cookie, cracker, cake, and pastry-making. In general, it is desirable for soft wheat to have a low flour protein concentration (less than 10%), whole grain hardness (rated less than 40) and sucrose solvent retention capacity (SRC, less than 89%) (Redinbaugh et al., 2013). Higher values for lactic acid SRC (greater than 87%) are desired (Redinbaugh et al., 2013). High softness equivalent (53 to 64%) and high flour yield (greater than 67.5%) (Redinbaugh et al., 2013) are also desired for soft wheat. A cookie diameter of 18.1 to 19.5 cm is desirable for soft wheat, as this produces superior confectionary products (Redinbaugh et al., 2013).

Laboratory analyses have been designed to evaluate quality more conveniently and less expensively than actually milling and baking products from the wheat flour. The USDA Soft Wheat Quality Laboratory recommends that soft wheat breeding programs focus on flour yield, sucrose SRC, lactic acid SRC, and softness equivalent, as these traits are highly heritable and easily measured on a large number of samples (Souza et al., 2012). In general, the growing environment currently plays a greater role in determining quality factors of wheat than the genetics, so improving the genetic stability of cultivars across environments is a major long-term goal in the wheat industry (Peterson et al., 1998).

Previous research studying the effects of harvest grain moisture on milling and baking qualities of wheat has revealed mixed results. One of the earliest studies carried out by Mangels and Stoa (1928) observed no differences in baking quality for hard wheat harvested at various stages of maturity ("dough, hard dough, glazed, normal ripe, and dead ripe"). A study of harvest grain moisture effects on SR and SW kernel texture, grain protein, and flour protein by Yamazaki (1976) also found no differences in the quality of grain harvested from 42.3 to 13.5% moisture. Scott et al. (1957) found that yield, test weight, and kernel weight of hard red winter wheat were optimized as grain was harvested closer to 40% moisture under field conditions but harvested by hand. Protein content was also highest at 40% moisture (Scott et al., 1957). However, only three cultivars were tested in only one location (Hays, Kansas) using only one of the two years since drought conditions and poor stands compromised the second year (Scott et al., 1957). A study of hard red spring wheat by Tipples (1980) reported that protein content was lowest at high grain moisture (50%) and protein increased as grain dried down. This study was performed over four years and one to four cultivars (depending on the year) in Manitoba, Canada (Tipples, 1980). Since protein is highly influenced by cultivar, fertility, and environment (Souza et al., 2004), variation between these two studies was expected. Tipples (1980) also observed more flour yield and less starch damage and water absorption as grain moisture decreased. Kirleis et al. (1982) studied one cultivar of SR wheat over two years at Lafayette, Indiana. The percentage of broken kernels was minimized when grain moisture was less than 27% prior to mechanical harvest. Milling rating (flour yield - flour ash x 100%) increased as harvest grain moisture decreased from 41.8 to 16.2%. Flour yield and cookie diameter were not affected by grain moisture. These results suggested that preferred milling and baking quality was achieved when harvest grain moisture was 30 to 35% (Kirleis et al., 1982). This relationship was very similar for both years, but more testing is needed across environments and modern cultivars.

Early-maturing wheat cultivars have not been extensively tested. Early-maturing cultivars are useful in avoiding both abiotic (e.g., drought, hail) and biotic stresses (e.g., pathogens, insects) that affect quality. Early-maturing wheat cultivars increase the possibility of an early harvest, which gives growers the option to double-crop following wheat in regions with short growing seasons. While growers typically harvest wheat at 14 to 16% grain moisture, harvesting earlier (22 to 24% moisture) could also help avoid environmental stresses. The combination of early-maturing wheat cultivars harvested at high grain moisture (i.e., harvested earlier than normal) would expand the opportunities to successfully produce double-crop soybean (*Glycine max* L.) in the northern half of Indiana and increase profitability. Our objectives were to determine the effects of harvest grain moisture (i.e., harvest timing) on the milling and the baking quality of wheat. We hypothesized that harvesting wheat early (at higher grain moisture levels) would increase the milling and baking quality of the grain.

2.3 Materials and Methods

2.3.1 Experimental Design

Ten soft winter wheat cultivars (Table 2.1) were planted October 3, 2011, and October 1, 2012. Row spacing was 16.5 cm within plots 3.7 m long by 1.2 m wide. Seeding rate was 3.7 million seeds per hectare. Nitrogen fertilizer (liquid, 28% N) was applied each year at a rate of 114 kg N per ha on February 25, 2012, and on February 20, 2013. Cultivars were arranged in a randomized complete block design with three replications. The study was located near West Lafayette, IN, in a field of Chalmers silty clay loam (fine-silty, mixed, superactive, mesic Typic Endoaquoll) in both years. Disease was not present to a significant level in 2012, and no fungicide was applied. In 2013, a minimal amount of head scab (caused by *F. graminearum*) was detected. Fungicides can increase grain protein (Baenziger et al., 1985), and thus, we did not apply fungicides in 2013.

2.3.2 Cultivar Selection

Cultivars were chosen for this study based on a number of factors, including maturity, quality and agronomic performance, and popularity with growers. Clark, though a comparatively older cultivar (developed 1988), is still commonly grown in Indiana and is considered the “standard of earliness” for Indiana wheat. The agronomic performance of this cultivar has been well-characterized. It has been used as a parent line by many breeders for the development of current cultivars. Branson was also commonly grown in Indiana. It is a common check cultivar used in both agronomic and quality research.

The experimental lines 9346A1—2 and 07290A1-12W were in development within the wheat breeding program at Purdue University (H.W. Ohm, personal communication, 2011) and were of interest for the performance potential.

Commercial lines Pio25R26, Pio25R62, and Pio25W43 were developed and released by Pioneer HI-BRED with good agronomic performance and consistently acceptable quality. These cultivars were popular with growers in Indiana and Michigan.

Soft white wheat cultivars E5011, E5024, and E6012 were recently released primarily for use in Michigan with better agronomic and quality performance over previously grown cultivars.

2.3.3 Grain Head Sampling

Target grain moisture was 40% down to 10% (g of water per g of dry grain x 100) with a target of 5 to 6 samples taken from each treatment within the moisture range (Table 2.1). Cultivars were monitored daily as grain moisture reached ≈40%, near physiological maturity. Approximately 150 heads were sampled randomly within the middle of each plot once target grain moisture levels were reached. Samples were harvested by hand and immediately placed in plastic bags to prevent moisture loss.

A subsample of 10 heads was threshed and weighed immediately after harvest sampling. The threshed grain was dried thoroughly at 60^{0}C and weighed to determine the gravimetric moisture content {[(fresh weight of grain - dry weight of grain) / (dry weight of grain)] x 100}. Remaining heads were weighed fresh and dried at 38^{0}C until reaching the target weight near 14% moisture. This temperature and target moisture level is standard when drying high-quality wheat, as this combination prevents excessive damage to the starch and grain protein (Kirleis et al., 1982). Grain head samples were removed from the dryer and weighed periodically to ensure the desired amount of moisture loss was achieved, which ranged from a few hours to nearly 24 hours. Grain head samples below 14% moisture were not dried further. Grain head samples were threshed and cleaned prior to quality analyses.

2.3.4 Milling and Baking Quality Analyses

Grain samples were analyzed for various milling and baking qualities at the USDA Soft Wheat Quality Lab (SWQL) in Wooster, Ohio. These qualities were whole grain hardness, whole grain protein, flour yield, flour protein, softness equivalent, lactic acid SRC, and sucrose SRC. Modified milling quality score, modified baking quality score, modified softness equivalent score, and estimated cookie diameter were also reported based on the fit of these parameter values to a standard regression model for each score (Finney and Andrews, 1986). Overall suitability of wheat grain for end-use applications was based on these evaluations. Samples were moistened or dried further to attain 14% moisture level in the grain 48 h prior to milling. Once the appropriate amount of water was added to the sample, the sample was placed on a chain-driven roller conveyor until the water was evenly dispersed throughout the sample.

Whole Grain Characteristics. Whole grain hardness and whole grain protein were measured using the DA7200 NIR spectrometer from Perten Instruments (Perten Instruments, Springfield, IL). Grain was then milled using the Quadrumat Junior Flour Mill. Milling occurred in a controlled environment, with the ambient temperature at 19 to 21°C and a relative humidity of 55 to 60%. Prior to this test, the mill was required to be operating, warm, and equilibrated to 36°C±1°C to ensure proper function. Flour yield is the first measurement made in milling and baking tests. The flour produced was used for the remainder of the analyses.

Flour Yield. Subsequent to milling, the product was then sifted using a Great Western Sifter Box. This sifter has two mesh screens (with openings of 471 µm and 181 µm) that separate the product into three classes. The first, which is the bran, stays above the 471 µm mesh screen. The second fraction, the “mids”, stays between 471 µm and 181 µm, while the finest particle class passes through the 181 µm screen. These products were then weighed to determine the flour yield. Flour yield (standard error = 0.964%) is calculated as follows:

Flour yield= [(grain weight – bran weight) / grain weight] x 100%

Flour Protein. Flour protein (standard error = 0.477%) was determined by near-infrared reflectance (NIR) using the Unity SpectraStar2400 NIR instrument calibrated by nitrogen combustion analysis using Elementar Nitrogen Analyzer. The NIR instrument output described the amount of nitrogen in the flour, which was multiplied by a factor of 5.7 and converted to percent protein, expressed on a 14% moisture basis (Redinbaugh et al., 2013).

Softness Equivalent. Softness Equivalent (standard error = 2.088%) was calculated from the fraction of the milled product that was in the mids (see “Flour Yield,” above). Softness Equivalent was calculated:

SE= [(flour weight – mids weight) / flour weight] x 100%.

Solvent Retention Capacity (SRC). Lactic acid SRC (standard error = 2.420%) and sucrose SRC (standard error = 2.790%) were tested as per the American Association of Cereal Chemists method AACC 56-11.

Milling and Baking Quality Scores. The combined milling and baking quality scores provide a quick view of the general quality of the sample. The grain sample was compared to the standard check values established by the SWQL and each score represented a standard adjustment of the parameter tested (e.g., softness equivalent). This was meant to provide a score that was independent of environmental influence. These formulas originate from the regression models developed by the SWQL, and have shown to be a reliable prediction tool for overall milling and baking quality (Finney and Andrews, 1986).

Modified Milling Quality Score (MMQS) = -282.08 + 4.971 × flour yield

Modified Softness Equivalent Score (MSES) = -98.66 + 2.827 × softness equivalent

Estimated Cookie Diameter (ECD) = 20.70654 - 0.1829355 × flour protein - 0.005519322 ×lactic acid SRC + 0.06379016 × softness equivalent - 0.03951647 × sucrose SRC

Modified Baking Quality Score (MBQS) = -129.74 + 14.267 × cookie diameter - 1.279 × sucrose SRC - 1.488 × flour protein + 0.891 × softness equivalent

2.3.5 Statistical Analyses

To study the effects of harvest grain moisture on quality, regression models were chosen based on the most appropriate fit to observe the change in quality parameters with grain moisture. Models were run across wheat type and years, and then run within wheat type and years. Five cultivars within SR and five cultivars within SW wheat were analyzed (Table 2.1). Regression analyses were conducted from low to high grain moisture. However, negative slopes are discussed in the inverse (i.e., quality increased as grain moisture decreased) and positive slopes are as well (i.e., quality decreased as grain moisture decreased). Linear, quadratic, and combined model regressions were run using the PROC GLM of SAS version 9.3 (SAS Institute, Cary, NC). Model effects were tested for significance ($P<0.05$) using the appropriate F-test. Selected models varied by parameter and growing season. Data could not be combined over years due to differences in climate and sampling dates for in-season data and heterogeneity of variance between years. Thus, years and wheat types will be discussed separately. Differences in the regression relationships of lactic acid SRC and grain moisture were detected among cultivars in 2013 for SR wheat (see section 2.4.2). All other regression relationships among quality parameters and grain moisture did not differ among cultivars within wheat type and year.

2.4 Results and Discussion

2.4.1 Growing Conditions

Mean monthly temperature was above normal and precipitation was below normal, during the 2011-12 growing season (Table 2.2). These conditions initiated the 2012 drought, which caused rapid grain moisture loss and early maturation of the wheat. Daily temperatures were high for most of the harvest sampling period, especially after the first five days (Fig. 2.1A). Almost no precipitation was received during the 20-day sampling period, with only a trace amount of rain falling on four occasions (Figs. 2.2A, 2.2B).

Mean monthly temperatures were close to normal and precipitation was above normal during the 2012-13 growing season, especially from green-up to maturation (Table 2.2). Maximum daily temperature was higher during the first half of the sampling period of 2013 compared to 2012; whereas, the second half of 2013 was lower than 2012

(Fig. 2.1A). For the majority of the sampling period, relative humidity was higher during 2013 than 2012 (Fig. 2.1B). Accumulation and frequency of precipitation was also greater in the 2013 sampling period than 2012 (Figs. 2.2A, 2.2.B).

2.4.2 Milling and Baking Quality

The quality parameters were grouped into the categories related to protein, texture, and overall milling and baking quality. Harvest moisture had little influence on most quality characteristics (Table 2.3) suggesting that the quality may at least be maintained by harvesting at high moisture.

Protein Characteristics

Grain moisture did not affect whole grain protein or flour protein, but lactic acid SRC increased quadratically (maximized at 20% moisture) as grain moisture decreased in SR wheat in 2012 (Table 2.3). Whole grain and flour protein means were 10.9% and 8.5%, respectively, for SR wheat (Table 2.4). In 2013, both lactic acid SRC (Table 2.3) and whole grain protein (Table 2.3, Fig. 2.3A) increased linearly as grain moisture decreased, while flour protein was not affected by grain moisture for SR wheat. Flour protein mean was 8.2% for SR wheat in 2013 (Table 2.4).

The response of individual cultivars was only different in 2013 within SR for lactic acid SRC. The regression slopes of Pio25R26 (slope=0.546; P=0.021) and Pio25R62 (slope=0.541; P=0.020) were similar to one another and were more positive than those of Branson, Clark, and 9346A1—2. The latter three cultivars did not differ from the overall regression for SR wheat. The general trend for each cultivar was the same; lactic acid SRC increased as grain moisture decreased.

Whole grain protein (Table 2.3, Fig. 2.3B) and flour protein (Table 2.3) of SW wheat decreased very slightly as grain moisture decreased in 2012. Lactic acid SRC was not affected for SW wheat in 2012 and averaged 73.9% (Table 2.4). During the 2013 growing season, no protein characteristics were affected by grain moisture in SW wheat. Whole grain protein, flour protein, and lactic acid SRC averaged 10.1%, 7.7%, and 85.3%, respectively, for SW wheat (Table 2.4).

The low protein values in this study were considered desirable for soft wheat products. It is desirable for soft wheat to have flour protein levels below 10%, and whole grain protein should be less than 11.5% (Redinbaugh et al., 2013). Whole grain protein means exceeded the standard for high-quality whole grain products of soft wheat over both years and grain types (Table 2.4). The desired lactic acid SRC level was greater than 87% (Redinbaugh et al., 2013). In this study, means of both SR wheat and SW wheat were unacceptable in 2012, but SR wheat was acceptable in 2013. Harvest moisture did not affect whole grain protein of one SR cultivar grown over two years in Indiana; though N fertilizer was not used (Kirleis et al., 1982). However, we applied N fertilizer (liquid, 28% N) at a rate of 114 kg N per hectare in February of both years. The mixed results in our study suggest that more testing may be needed to discern the relative contributions of grain moisture and N fertilization to whole grain and flour protein concentration. While differences in the weather did not affect the grain protein concentration, the hot, dry conditions in 2012 may have been detrimental to grain protein quality.

However, this study showed that lactic acid SRC increased as grain moisture decreased for SR wheat across both test years. These results were consistent with the heritability of the respective traits; gluten strength is considered to be highly heritable whereas protein concentrations are not (Souza et al., 2012). It is important for end users to consider both the protein quantity (whole grain and flour protein concentrations) and protein quality (measured by the lactic acid SRC test, which measures the strength of the gluten). Protein quantity may not be related to grain moisture, but quality of protein may be affected.

Texture Characteristics

Whole grain hardness of SR wheat was not related to grain moisture in 2012 (Table 2.3) and averaged 32.9 (Table 2.4). However in 2013, whole grain hardness of SR wheat decreased linearly as grain moisture decreased (Table 2.3, Fig. 2.4A). Softness equivalent had no correlation to grain moisture in 2012 and 2013 for SR wheat (Table 2.3), and means were 50.8% and 56.1%, respectively (Table 2.4). Sucrose SRC of SR wheat increased quadratically (maximized at 24% moisture) as grain moisture decreased in 2012, but showed no relationship to grain moisture in 2013 (Table 2.3) and averaged 87.6% in 2013 (Table 2.4).

Whole grain hardness of SW wheat decreased quadratically (minimized at 18% moisture) in 2012 (Table 2.3, Fig. 2.4B). Whole grain hardness decreased linearly as grain moisture decreased in 2013 (Table 2.3, Fig. 2.4B). Grain moisture did not affect softness equivalent in 2012 (mean of 55.5%, Tables 2.3 and 2.4). However, softness equivalent increased linearly with decreasing grain moisture of SW wheat in 2013 (Table 2.3). Grain moisture did not affect sucrose SRC in 2012 and 2013 (~85%, Table 2.4).

Softness equivalent means were desirable for soft wheat products across both years for SW wheat, since values were within 53 to 64% (Redinbaugh et al., 2013). The softness equivalent mean for SR wheat was desirable in 2013, but was below the desired level in 2012 (Table 2.4). Sucrose SRC values of 89% and below are considered desirable for most soft wheat products (Redinbaugh et al., 2013). Means in this study were desirable across both grain types and years for sucrose SRC for most products. These results suggested that higher moisture harvest did not have a negative effect on texture characteristics of soft wheat.

Overall Milling and Baking Quality

The effects of grain moisture on overall quality were mixed. Grain moisture did not impact modified milling quality score (MMQS) or flour yield for either grain type in 2012 and 2013 (Table 2.3) with means reported in Table 2.4. The MMQS was comparatively lower in 2013 for both grain types; whereas, flour yield was higher than 2012 (Table 2.4).

Modified baking quality score (MBQS) of SR wheat decreased quadratically (minimized at 20% moisture) as grain moisture decreased to 2012 (Table 2.3, Fig. 2.5A), but grain moisture did not alter MBQS in 2013 (mean of 70.7, Table 2.4). Modified softness equivalent score (MSES) was not correlated to grain moisture for SR wheat in 2012 and 2013 (Table 2.3), with respective means of 69.5 and 74.1 (Table 2.4). Estimated cookie diameter (ECD) for SR wheat decreased quadratically (minimized at 20% moisture) as grain moisture decreased in 2012 (Table 2.3, Fig. 2.6A), but ECD was not related to grain moisture in 2013 (Tables 2.3 and 2.4). Higher lactic acid SRC and sucrose SRC values for SR wheat in 2012 as grain moisture decreased contributed to the decrease in estimated cookie diameter.

Grain moisture did not affect MBQS of SW wheat in 2012 (mean of 91.0), but MBQS increased linearly as grain moisture decreased in 2013 (Table 2.3, Fig. 2.5B).

Grain moisture of SW wheat did not affect MSES in 2012 and averaged 82.8 (Table 2.4). However, MSES of SW wheat increased linearly as grain moisture decreased in 2013 (Table 2.3). Grain moisture did not affect ECD in 2012 (Table 2.3) with a mean of 19.2 cm (Table 2.4). As grain moisture decreased, ECD increased linearly in 2013 for SW wheat (Table 2.3, Fig. 2.6B). The increase in softness equivalent contributed to the increase in estimated cookie diameter as SW wheat grain moisture decreased in 2013.

Flour yields were below the desired value of 67.5% for SR wheat in both years (Table 2.4). Flour yield was unacceptable for SW wheat in 2012, but was acceptable in 2013. Both of these means only deviated less than 1% from the desired target. Scores above 60 for MMQS, MBQS, and MSES are considered acceptable for soft wheat products (Redinbaugh et al., 2013). Mean values for MMQS were undesirable across years and grain types. The means of MBQS met the target for SR wheat and exceeded the target for SW wheat (Table 2.4). Mean MSES were good for SW wheat in both years and for SR wheat in 2013 (Table 2.4). In 2012, MSES for SR wheat was slightly below the desired level (Table 2.4). Across grain types and years, the means of ECD were within the accepted range of 18.1 to 19.5 cm.

Kirleis et al. (1982) showed that optimal milling quality was achieved at 30 to 35% grain moisture for one cultivar across two years. Our study showed mixed results over years and grain types. Flour yield was lower in 2012 than in 2013, which may be linked to the drought conditions during grain fill in 2012. Deficit moisture reduced starch partitioning into the grain (Jenner et al., 1991). However, the lack of relationship of flour yield and MMQS to grain moisture suggested that milling quality may at least be maintained when grain was harvested at high moisture. Mixed results for MBQS are indicative of its mathematical relationship to flour protein, which was not highly stable over years and environments (Souza, 2004). Grain moisture only influenced the MSES of SW wheat in 2013. The MSES of the remaining combinations of year and type(s) was very near to or above the desired level, which confirmed that harvesting at high grain moisture did not negatively affect MSES. In previous research, actual cookie diameter was largely unaffected by grain moisture level for one wheat cultivar (Kirleis et al., 1982). A study of this characteristic using actual bake tests rather than predicted regressions to measure cookie diameter would be useful for discerning the full effect of grain moisture on cookie quality. It is also likely that ECD may not be as stable across environments as other parameters, as one of its components is flour protein concentration, which is known to have low heritability (Finney and Andrews, 1986). This may have also contributed to the mixed results.

2.5 Conclusions

Overall, the results of this study supported our hypothesis that the milling and baking quality of wheat was not detrimentally impacted by harvesting grain at high moisture. Flour yield, one of the most important quality parameters, did not change as a result grain moisture across the two years of the five SR cultivars and the five SW cultivars. This suggests that flour yield could at least be maintained if grain was harvested at high moisture. Because it is mathematically related to flour yield, MMQS also remained unaffected by grain moisture. Protein quality, as measured by lactic acid SRC, increased as grain moisture decreased in SR wheat (peak near 20% grain moisture in 2012 and linear increase in 2013). Though, lactic acid SRC was still acceptable in both wheat types when grain was harvested at higher grain moisture. Other parameters showed mixed results over years and grain types. In most cases, quality increased or remained unchanged when grain moisture was high. Individual cultivar response did not differ within each wheat type and year except for lactic acid SRC in SR wheat harvested in 2013. Thus, the effects of harvest grain moisture were very consistent across cultivars and wheat types within a given year.

Harvesting early-maturing wheat cultivars at high grain moisture did not negatively influence quality. In general, grain at 22 to 24% moisture displayed favorable milling and baking quality for most parameters. It would also be feasible for a commercial grower to harvest at this grain moisture using standard equipment. However, mechanical harvesting would likely cause more kernel damage, resulting in reduced grain quality. In 2012, drying occurred very quickly, and harvesting grain at higher (24%) moisture gained only about 2.5 calendar days over harvesting at normal (14%) moisture. However, the higher moisture harvest in 2013 gained about 5 days over the normal moisture harvest. In years with frequent rainfall during harvest, it could be advantageous to harvest grain early to avoid stress to the wheat crop, as well as plant the subsequent soybean crop earlier. It is important to acknowledge that practices in this study were less damaging than the mechanical harvesting and conditioning practices used by commercial growers. Potential research efforts in the future could be directed to studies using commercial harvest and handling methods, as well as the application of fungicides. Fungicides have been shown to increase grain protein levels (Baenziger et al., 1985), as well as increase or maintain grain moisture levels. Studies could also be carried out at more northern latitudes, as the opportunity for double-cropping soybean could be increased. Studies regarding the economic implications of high-moisture harvest could also be useful to growers to food-grade wheat.

2.6 References

Finney, P.L. (1990). Flour, milling, and end-use quality of Ohio wheat. p.78-87. In J.E. Beuerlein (ed.) Profitable wheat management. Ohio State University Extension Bulletin 811.

Finney, P.L. and L.C. Andrews. (1986). Revised Mircotesting for Soft Wheat Quality Evaluation. Cereal Chemistry 63(3):177-182.

Gaines, C.S. (2004). Prediction of Sugar-Snap Cookies Diameter Using Sucrose Solvent Retention Capacity, Milling Softness, and Flour Protein Content. Cereal Chemistry 81(4):549-552.

Jenner, C.F., T.D. Ugalde, and D. Aspinall. (1991). The Physiology of Starch and Protein Deposition in the Endosperm of Wheat. Australian Journal of Plant Physiology 18:211-226.

Kirleis, A.W., T.L. Housley, A.M. Emam, F.L. Patterson, and M.R. Okos. (1982). Effect of Preripe Harvest and Artificial Drying on the Milling and Baking Quality of Soft Red Winter Wheat. Crop Science 22:871-876.

Kumar, S., V. Sharma, S. Chaudhary, A. Tyagi, P. Mishra, A. Priyadarshini, and A. Singh. (2012). Genetics of flowering time in bread wheat *Triticum aestivum*: complementary interaction between vernalization-insensitive and photoperiod-insensitive mutations imparts very early flowering habit to spring wheat. Journal of Genetics 91(1):33-47.

Mangels, C.E. and T.E. Stoa. (1928). Effect of stage of maturity on composition and baking quality of Marquis wheat. Cereal Chemistry 5:385-394.

Mason, H, A. Navabi, B. Frick, J. Donovan, D. Niziol, and D. Spaner. (2007). Does growing Canadian Western Hard Red Spring wheat under organic management alter its breadmaking quality? Renewable Agriculture and Food Systems 22(3):157-167.

McKendry, A. L., D.N. Tague, and K. Ross. (2001). Comparative Effects of 1BL.1RS and 1AL.1RS on Soft Red Winter Wheat Milling and Baking Quality. Crop Science 41:712-720.

Peterson, C.J., R.A. Graybosch, D.R. Shelton, and P.S. Baenziger. (1998). Baking quality of hard winter wheat: response of cultivars to environment in the Great Plains. Euphytica 100:157-162.

Ohm, H.W. (2011). Personal communication.

Redinbaugh, M.G., B.K. Baik, and A. Sturbaum. (2013). Soft Wheat Quality Laboratory 2013 Annual Report. Retrieved from <https://www.ars.usda.gov/SP2UserFiles/Place/36070500/SWQL%20AR%20Final%202013%203.11%20and%20attchmts.pdf>.

Scott, G.E., E.G. Heyne, and K.F. Finney. (1957). Development of the Hard Red Winter Wheat Kernel in Relation to Yield, Test Weight, Kernel Weight, Moisture Content, and Milling and Baking Quality. Agronomy Journal 49(9):509-513.

Souza, E.J., C. Sneller, M.J. Guttieri, A. Sturbaum, C. Griffey, M. Sorrells, H. Ohm, and D. VanSanford. (2012). Basis for Selecting Soft Wheat for End-Use Quality. Crop Science 52:21-31.

Souza, E.J., J.M. Martin, M.J. Guttieri, K.M. O'Brien, D.K. Habernicht, S.P. Lanning, R. McLean, G.R. Carlson, and L.E. Talbert. (2004). Influence of Genotype, Environment, and Nitrogen Management on Spring Wheat Quality. Crop Science 44:425-432.

Tipples, K.H. (1980). Effect of immaturity on the milling and baking quality of red spring wheat. Canadian Journal of Plant Science 60:357-369.

Yamazaki, W.T. (1976). Soft Wheat Quality of Preripe Harvested Wheat. Crop Science 16:572-574.

Table 2.1.Cultivars and respective grain color, grain hardness, release year, heading date, and sampling date range for the 2011-12 and 2012-13 growing seasons. Cultivars were sampled as grain moisture decreased from approximately 40 to 10% at West Lafayette, Indiana.

				2011-12 Season		**2012-13 Season**	
Line	**Grain Color**	**Grain Hardness**	**Release Year**	**Heading Date**	**Sampling Range**	**Heading Date**	**Sampling Range**
Branson	red	soft	2005	4/24	5/31 to 6/11	5/15	6/19 to 7/3
Clark	red	soft	1988	4/24	5/31 to 6/11	5/15	6/19 to 7/3
9346A1--2	red	soft	nr†	4/24	5/31 to 6/12	5/16	6/20 to 7/3
Pio25R26	red	soft	1996	4/29	6/7 to 6/14	5/19	6/27 to 7/10
Pio25R62	red	soft	2007	4/26	6/7 to 6/11	5/17	6/21 to 7/3
07290A1-12W	white	soft	nr	4/25	6/5 to 6/13	5/16	6/20 to 7/3
Pio25W43	white	soft	2007	4/26	6/5 to 6/12	5/17	6/21 to 7/3
E6012	white	soft	2011	4/27	6/6 to 6/12	5/18	6/24 to 7/3
E5011	white	soft	2010	5/3	6/12 to 6/19	5/20	6/27 to 7/10
E5024	white	soft	2011	5/3	6/12 to 6/19	5/20	6/27 to 7/10

†nr = not released.

Table 2.2. Mean monthly temperature and precipitation during the 2011-12 and 2012-13 growing seasons (October-July), with deviations from the 30-yr normal (1981-2010). No data are shown for July of the 2011-2012 season, as harvest was completed in June. Data were collected at West Lafayette, Indiana.

	2011-2012 Season				**2012-2013 Season**			
Month	**Mean Air Temp.†**	**Dev.‡**	**Precip.§**	**Dev.**	**Mean Air Temp.**	**Dev.**	**Precip.**	**Dev.**
	---------°C---------		------mm------		----------°C--------		------mm------	
October	12.5	0.8	26.1	-51.4	10.8	-0.9	83.3	5.8
November	8.4	3.0	68.6	-13.7	4.8	-0.6	14.0	-68.3
December	2.1	3.9	118.2	56.0	3.9	5.7	80.7	18.5
January	-1.0	3.1	88.0	39.2	-1.9	2.2	111.5	62.7
February	1.0	2.8	26.1	-21.1	-1.8	0.0	61.4	14.2
March	13.2	9.3	49.0	-17.3	0.7	-3.2	23.7	-42.6
April	11.2	0.7	27.0	-63.9	9.6	-0.9	160.5	69.6
May	19.6	3.2	69.8	-51.1	18.1	1.7	77.2	-43.7
June	22.2	0.6	19.6	-84.3	21.8	0.2	105.9	2.0
July	-----	---	-----	---	21.6	-1.4	68.3	-38.4
Total			492.4	-207.6			786.5	-20.2

†Temp. = Temperature.

‡Dev. = Deviation from 30-yr normal (1981-2010) for temperature or precipitation based on preceding column.

§Precip. = Precipitation.

Table 2.3. Regression relationships between various quality parameters and grain moisture across soft white and soft red wheat grain types sampled in 2012 and 2013. The combined model (linear + quadratic) described the significant relationships in 2012, and the linear model described the significant relationships in 2013. Samples were collected as grain moisture decreased from approximately 40 to 10% at West Lafayette, Indiana. Regression analyses were conducted from low to high grain moisture. However, negative slopes are discussed in the inverse (i.e., quality increased as grain moisture decreased) and positive slopes are as well (i.e., quality decreased as grain moisture decreased).

Quality	**Soft Red**				**Soft White**			
	Intercept	**Moist**	**Moist^2**	**R^2**	**Intercept**	**Moist**	**Moist^2**	**R^2**
2012								
Whole Grain Protein	-	ns	ns	-	10.18	-0.096*	ns	0.05
Flour Protein	-	ns	ns	-	8.12	-0.114*	0.003*	0.07
Lactic Acid SRC†	78.93	ns	-0.030*	0.11	-	ns	ns	-
Whole Grain Hardness	-	ns	ns	-	31.84	-1.309**	0.035***	0.17
Softness Equivalent	-	ns	ns	-	-	ns	ns	-
Sucrose SRC†	83.49	0.457**	0.010**	0.13	-	ns	ns	-
Flour Yield	-	ns	ns	-	-	ns	ns	-
MMQS‡	-	ns	ns	-	-	ns	ns	-
MBQS‡	80.08	-1.175*	0.028*	0.09	-	ns	ns	-
MSES‡	-	ns	ns	-	-	ns	ns	-
ECD‡	18.69	ns	0.001*	0.08	-	ns	ns	-
2013								
Whole Grain Protein	11.42	-0.023***	-	0.12	-	ns	-	-
Flour Protein	-	ns	-	-	-	ns	-	-
Lactic Acid SRC†	106.04	-0.475***	-	0.16	-	ns	-	-
Whole Grain Hardness	18.92	0.276***	-	0.19	13.25	0.362***	-	0.30
Softness Equivalent	-	ns	-	-	62.56	-0.232**	-	0.12
Sucrose SRC†	-	ns	-	-	-	ns	-	-
Flour Yield	-	ns	-	-	-	ns	-	-
MMQS‡	-	ns	-	-	-	ns	-	-
MBQS‡	-	ns	-	-	87.80	-0.375*	-	0.05
MSES‡	-	ns	-	-	92.41	-0.657**	-	0.12
ECD‡	-	ns	-	-	19.44	-0.015*	-	0.07

*, **, and *** represent significance at P=0.05, 0.01, and 0.001; respectively. ns = not significant.

†SRC= solvent retention capacity

‡Quality scores are abbreviated as follows: MMQS= modified milling quality score; MBQS= modified baking quality score; MSES= modified softness equivalent score; ECD= estimated cookie diameter

Table 2.4. Mean and ranges of qualities compared to quality standards. Samples were collected as grain moisture decreased from approximately 40 to 10% at West Lafayette, Indiana, in 2012 and 2013. Range of quality values does not necessarily match the range of grain moisture.

Quality	**Quality Standard†**	**Soft Red**		**Soft White**	
		Range	**Mean**	**Range**	**Mean**
2012					
Grain Moisture (%)	**-**	**6.7-39.6**	**23.3**	**7.0-35.9**	**20.3**
Whole Grain Protein (%)	<11.5	9.2-12.7	10.9	8.2-10.4	9.6
Flour Protein (%)	<10	7.2-10.0	8.5	5.9-8.2	7.1
Lactic Acid SRC‡ (%)	>87	67.5-96.2	84.3	66.1-88.7	73.9
Whole Grain Hardness	<40	21.5-42.8	32.9	11.4-37.6	20.9
Softness Equivalent (%)	53-64	46.5-56.5	50.8	48.1-62.9	55.5
Sucrose SRC‡ (%)	<89	82.0-93.8	88	80.9-90.8	85.2
Flour Yield (%)	>67.5	60.7-67.8	64.8	63.9-68.6	66.8
MMQS§	>60	35.9-71.4	56.4	52.0-75.3	66.3
MBQS§	>60	54.2-88.5	70.5	64.3-115.1	91
MSES§	>60	57.6-85.8	69.5	62.0-103.8	82.8
ECD§ (cm)	18.8±0.7	17.9-19.0	18.4	18.3-20.0	19.2
2013					
Grain Moisture (%)	-	**10.8-42.8**	**24.2**	**8.0-41.9**	**22.8**
Whole Grain Protein (%)	<11.5	9.6-12.7	10.9	9.1-11.9	10.1
Flour Protein (%)	<10	7.4-9.7	8.2	6.5-10.7	7.7
Lactic Acid SRC‡ (%)	>87	78.0-121.0	94.5	75.0-94.5	85.3
Whole Grain Hardness	<40	14.4-38.1	25.6	9.2-31.6	21.52
Softness Equivalent (%)	53-64	50.3-61.3	56.1	46.4-66.1	57.3
Sucrose SRC‡ (%)	<89	80.9-93.9	87.6	81.5-94.1	85.8
Flour Yield (%)	>67.5	62.6-70.9	67.1	64.3-70.9	68.4
MMQS§	>60	31.2-72.4	53.8	39.9-72.4	60.2
MBQS§	>60	54.0-87.4	70.7	51.9-100.8	79.2
MSES§	>60	57.7-88.8	74.1	46.7-102.4	77.4
ECD§ (cm)	18.8±0.7	18.2-19.3	18.8	18.2-19.9	18.9

†Redinbaugh et al., 2013.

‡SRC= solvent retention capacity

§Quality scores were abbreviated as follows: MMQS= modified milling quality score; MBQS= modified baking quality score; MSES= modified softness equivalent score; ECD= estimated cookie diameter

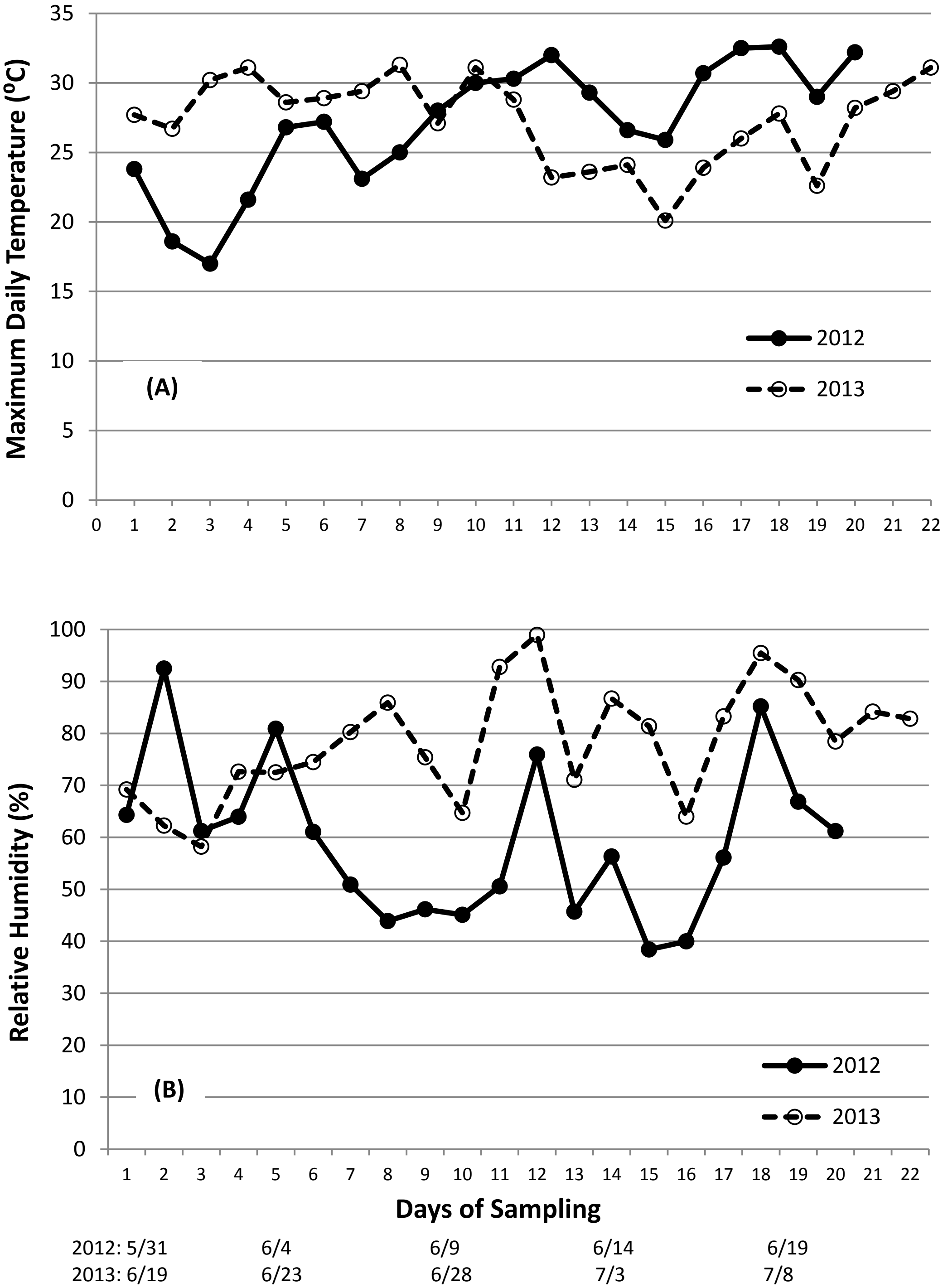

Figure 2.1. (A) Maximum daily temperature and (B) average relative humidity during the harvest sampling period, which lasted 20 days in 2012 (May 31 to June 19) and 22 days in 2013 (June 19 to July 10) at West Lafayette, Indiana.

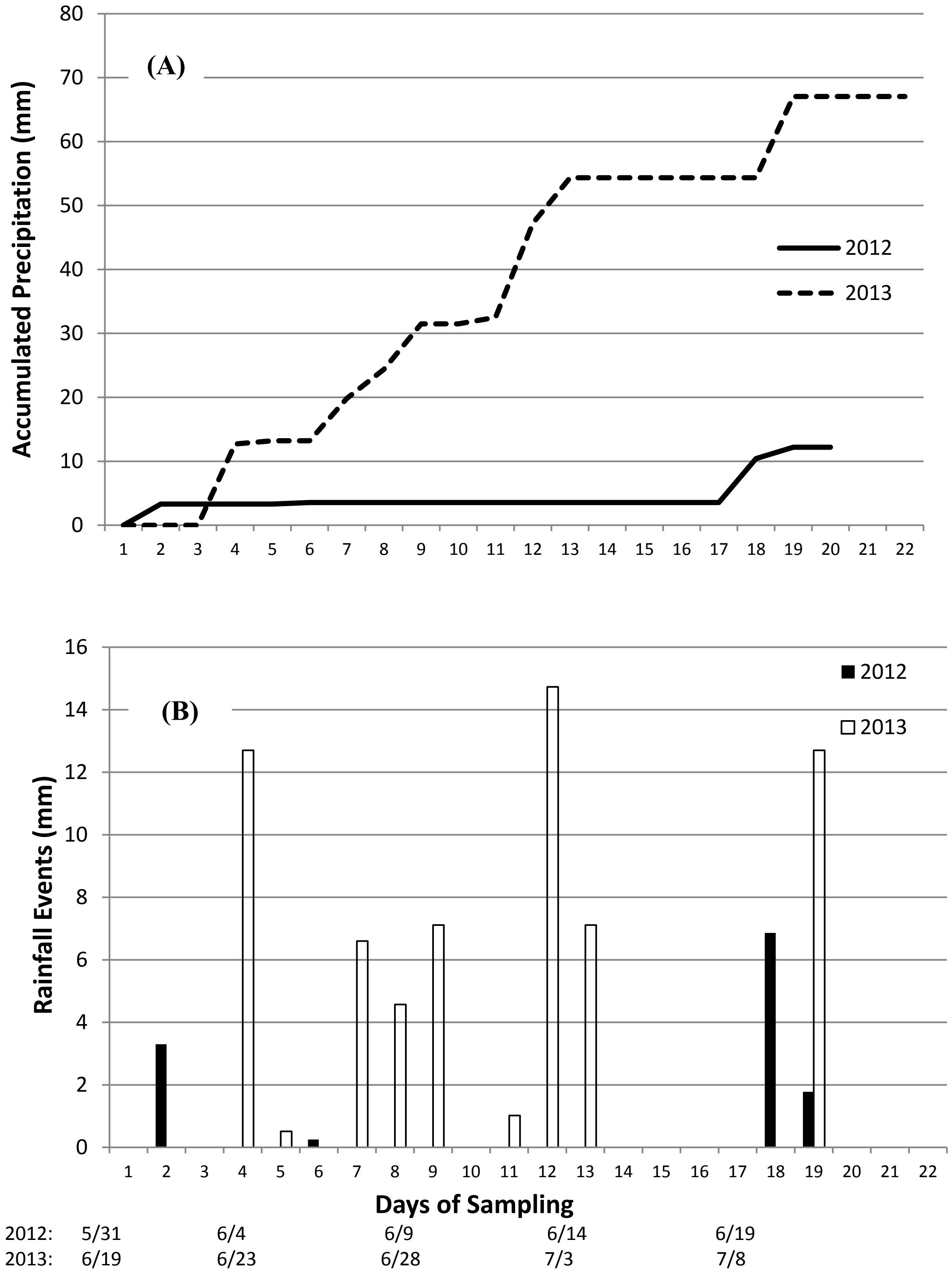

Figure 2.2. (A) Accumulated precipitation and (B) rainfall events during the harvest sampling period, which lasted 20 days in 2012 (May 31 to June 19) and 22 days in 2013 (June 19 to July 10) at West Lafayette, Indiana.

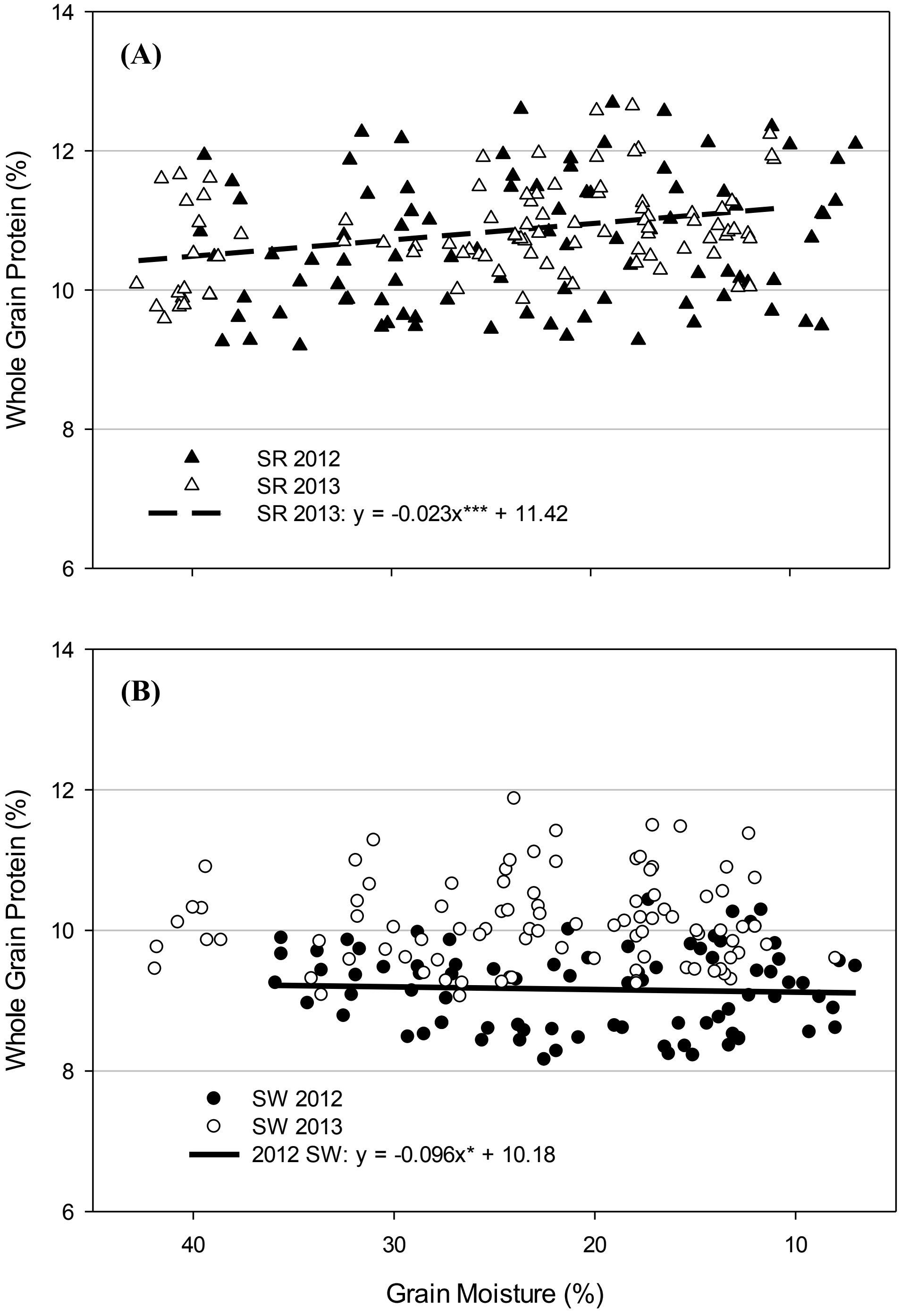

Figure 2.3. Grain moisture effects on (A) whole grain protein of soft red (SR) wheat, and (B) whole grain protein of soft white (SW) wheat. Ten cultivars were sampled as grain moisture decreased from approximately 40 to 10% at West Lafayette, Indiana, in 2012 and 2013. *, **, and *** represent significance at P=0.05, 0.01, and 0.001; respectively.

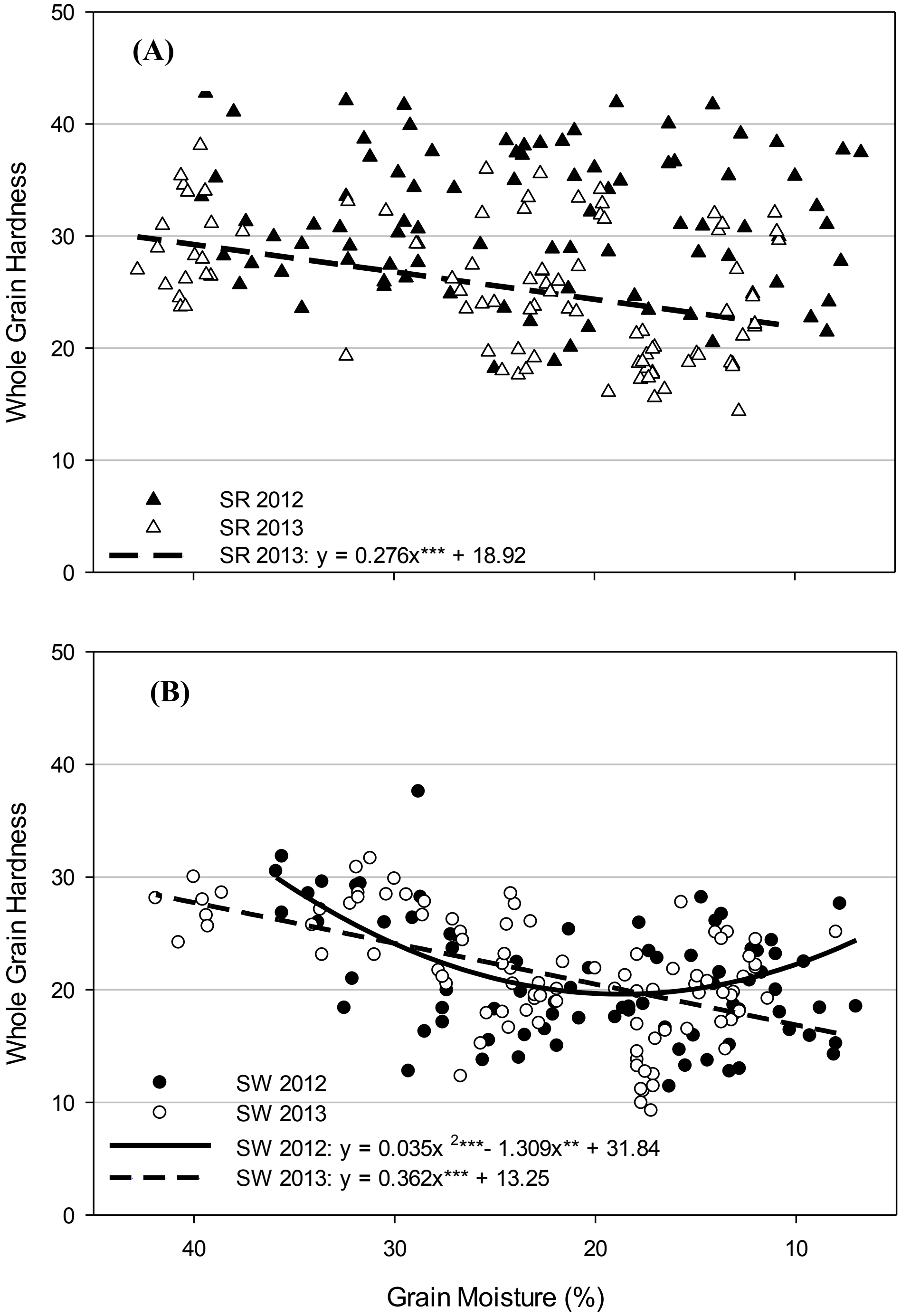

Figure 2.4. Grain moisture effects on (A) whole grain hardness of soft red (SR) wheat, and (B) whole grain hardness of soft white (SW) wheat. Ten cultivars were sampled as grain moisture decreased from approximately 40 to 10% at West Lafayette, Indiana, in 2012 and 2013; *, **, and *** represent significance at P=0.05, 0.01, and 0.001; respectively.

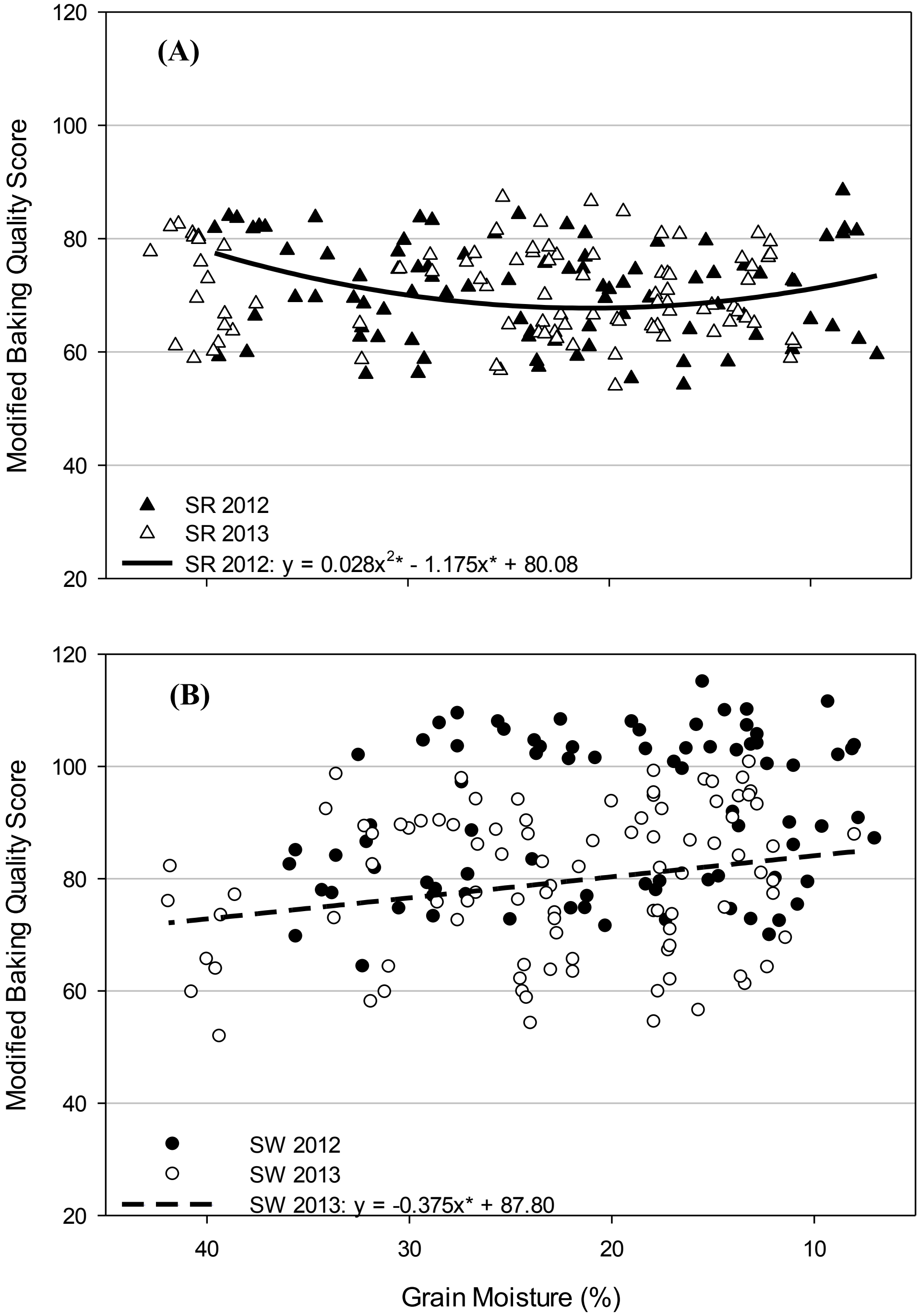

Figure 2.5. Grain moisture effects on (A) modified baking quality score of soft red (SR) wheat, and (B) modified baking quality score of soft white (SW) wheat. Ten cultivars were sampled as grain moisture decreased from approximately 40 to 10% at West Lafayette, Indiana, in 2012 and 2013; *, **, and *** represent significance at P=0.05, 0.01, and 0.001; respectively.

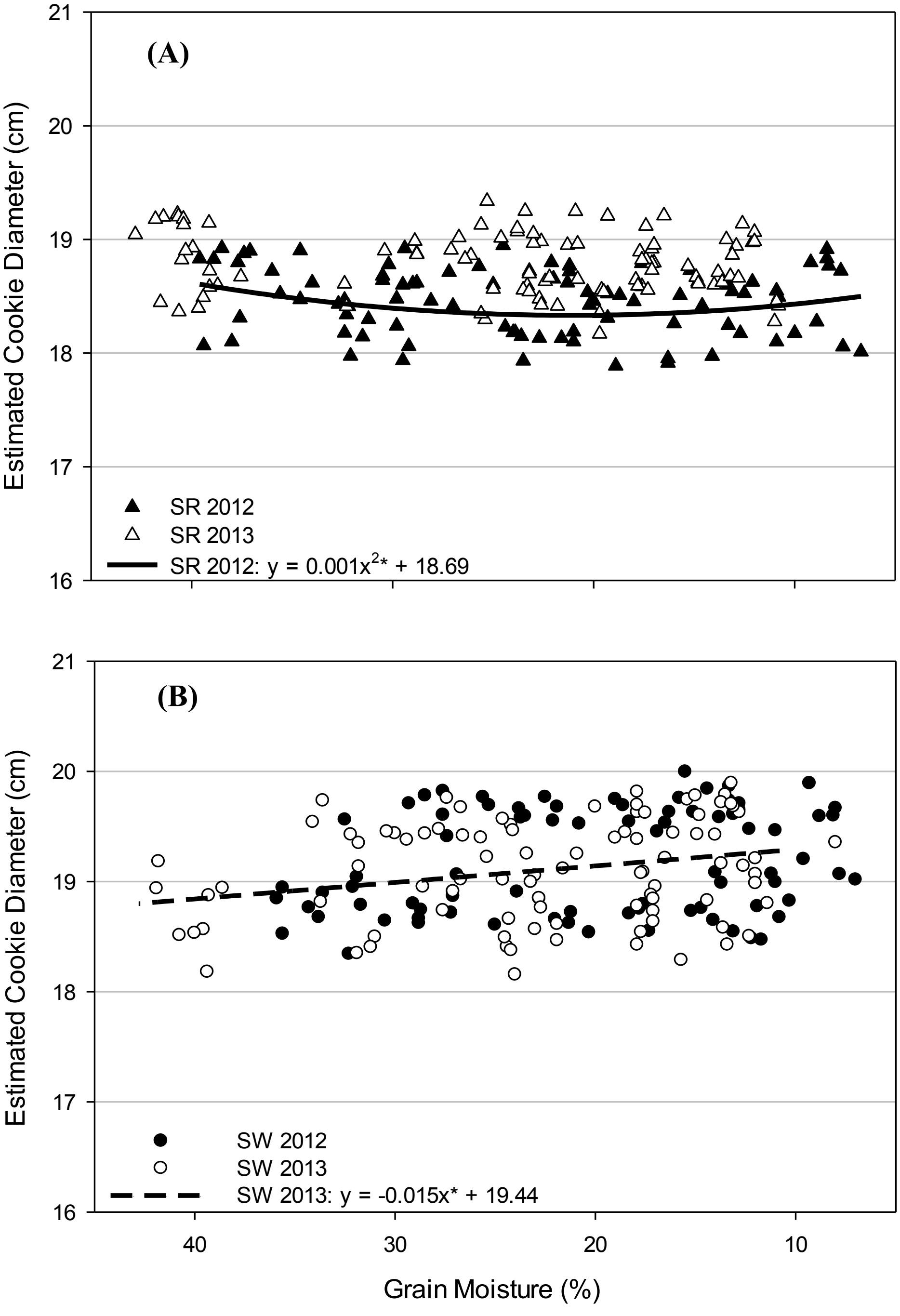

Figure 2.6. Grain moisture effects on (A) estimated cookie diameter of soft red (SR) wheat, and (B) estimated cookie diameter of soft white wheat. Ten cultivars were sampled as grain moisture decreased from approximately 40 to 10% at West Lafayette, Indiana, in 2012 and 2013; *, **, and *** represent significance at P=0.05, 0.01, and 0.001; respectively.

CHAPTER 3. GERMINATION POTENTIAL AND DRY-DOWN OF WHEAT AS RELATED TO GRAIN MOISTURE AND GROWING DEGREE DAYS

3.1 Abstract

As global demand increases, it is essential to increase the quality and efficiency of crop production. Harvesting wheat (*Triticum aestivum* L.) early provides an opportunity for increased grain quality, and it may also allow the grower to double-crop soybean (*Glycine max* L.) after wheat more effectively. Our objectives were to determine the effects of harvest grain moisture on germination of seed wheat and to develop a model to predict dry-down of wheat. We hypothesized that harvesting wheat early (at higher grain moisture levels) would increase the germination of wheat and that growing degree days (GDD) would be a reliable parameter to predict dry-down. Five soft red and five soft white winter wheat cultivars were grown at West Lafayette, IN, over two years. Grain was sampled by hand as drying progressed from 40 to 10% moisture. Germination was unaffected by high grain moisture at harvest except for soft red wheat in 2013, in which germination increased as grain moisture decreased. Both wheat types showed a strong linear decrease in grain moisture as GDD accumulated, but differed between years due to opposing weather patterns. While the drought conditions in 2012 caused a grain moisture loss of 2.1% per 10 accumulated GDD, relatively cooler, wetter conditions in 2013 caused a grain moisture loss of 1.4% per 10 accumulated GDD.

3.2 Introduction

Wheat (*Triticum aestivum* L.) production steadily increased in recent years with more arable land area planted to it than any other crop (FAO, 2010). As the global demand for commodity crops rises, greater production efficiency has become increasingly important. In the eastern Corn Belt, many growers of wheat also produce soybean (*Glycine max* L.). Double-cropping soybean following wheat is an excellent way to increase field efficiency, but growers must weigh the costs and benefits of this system.

Harvesting wheat early provides more opportunities for growers to take advantage of the wheat-soybean double-crop system. Early harvest is especially helpful at more northern latitudes, where planting soybean following wheat harvest is not always profitable. Early harvest may also increase grain quality (see Chapter 2), another advantage for the grower. However, growers of wheat seed may have concerns regarding the effects of high grain moisture on the viability of their seed. Management of this system also requires additional effort for the grower, and timing of wheat harvest and subsequent soybean planting are common concerns. More growers could increase their productivity if wheat could be harvested earlier. The longer season would then be available for the soybean crop. Utilizing early-maturing wheat varieties would also increase the season length, especially in combination with an early harvest.

Harvesting wheat early, at high grain moisture, has been shown to effect seed storage life, seed germination, and seedling vigor. More mature seed has a longer storage life (Kidd and West, 1919). Scott et al. (1957) confirmed this finding and also reported better seedling vigor with more mature seeds of three hard red winter wheat cultivars analyzed in one year in Kansas. Grain moisture ranged from 73 to 7%. However, this study reported that seed harvested at high moisture germinated faster (Scott et al., 1957).

Studies regarding the effects of harvest grain moisture on the germination of early-maturing cultivars are limited. Early-maturing wheat is susceptible to damage by late spring freezes. However, early-maturing cultivars are useful in avoiding other abiotic (e.g., drought, excessive rainfall,) and biotic stresses (e.g., pathogens, insects) that affect germination. One of the most prevalent biotic stresses in the eastern Corn Belt is head scab. Head scab can reduce germination potential even with low levels of infection (Bergstrom, 1993). However, this decrease may be mitigated with favorable post-harvest management practices. It has been observed in several studies that germination of infected seed increases after a period of storage, as the viability of seed-borne fungal spores decreases during this period (Bergstrom, 1993, and Gilbert, Tekauz, and Woods, 1997). In addition, Gilbert et al. (1997) reported that germination of infected seeds increased when the seed was stored at a lower, controlled temperature (5°C) compared to storage at ambient temperature.

Climatic conditions during the vegetative and grain fill periods of wheat have been studied at length, but the effects of these conditions after physiological maturity is limited. High relative humidity and frequent rainfall after physiological maturity pose a significant threat to germination potential of wheat. Imbibition of water before wheat harvest increases the alpha-amylase activity in the kernel thereby degrading the starch in the seed (Humphreys and Noll, 2002). Starch was a major energy source for germination, and thus, the germination potential is severely reduced (Humphreys and Noll, 2002). This process of pre-harvest sprouting (PHS) is a common problem for soft white wheat cultivars; whereas, soft red wheat cultivars are partially to completely resistant to PHS (Groos et al., 2002).

The determination of wheat harvest is often a subjective decision based on experience of a grower and the “feel” of the grain head in a grower’s hand. Other grain crop harvests are also somewhat subjective, but relationships of crop readiness for harvest in corn (*Zea mays*) have been related to climatic conditions after reaching physiological maturity (Cavalieri and Smith, 1985). In other words, the prediction of grain moisture loss or grain dry-down as it was related to temperature and rainfall. In wheat, effects of climatic conditions during the vegetative and grain fill periods have been studied at length, but effects of these conditions after the grain has reached physiological maturity has not. In corn, dry-down rates after physiological maturity may be estimated by using growing degree days (GDDs) (Cavalieri and Smith, 1985). Growers could predict the readiness of the crop as it related to current conditions and the weather forecasted in the days to come, and thus, make informed decisions for optimizing harvest. Similar predictions in wheat would be very useful, especially as growers consider double-cropping soybean. In addition, it has been documented that wheat loses test weight after every rainfall event that occurs post-physiological maturity (Lloyd et al., 1999).

Early-maturing wheat cultivars increase the possibility of an early harvest, which gives growers the option to double-crop following wheat in regions with short growing seasons. While growers typically harvest wheat at 13 to 15% grain moisture, harvesting earlier (22 to 24% moisture) could also help avoid environmental stresses (McNeill et al., 2008). The combination of early-maturing wheat cultivars harvested at high grain moisture (i.e., harvested earlier than normal) would expand the opportunities to successfully produce double-crop soybeans in the northern half of Indiana and increase profitability. Our objectives were to determine the effects of grain moisture (i.e., harvest timing) on the germination potential of wheat and to develop a model to predict dry-down of wheat. We hypothesized that harvesting wheat early (at higher grain moisture levels) would improve germination due to less exposure to environmental fluctuations (e.g., temperature, rainfall). According to previous dry-down models of corn, we hypothesize that best relationship for wheat predictions would be based on GDD.

3.3 Materials and Methods

3.3.1 Experimental Design

Ten soft winter wheat cultivars and (Table 3.1) were planted October 3, 2011, and October 1, 2012. Row spacing was 16.5 cm within plots 3.7 m long by 1.2 m wide. Seeding rate was 3.7 million seeds per hectare. Nitrogen fertilizer (liquid, 28% N) was applied each year at a rate of 114 kg N per ha on February 25, 2012, and on February 20, 2013. Cultivars were arranged in a randomized complete block design with three replications. The study was located near West Lafayette, IN, in a field of Chalmers silty clay loam (fine-silty, mixed, superactive, mesic Typic Endoaquoll) in both years.

3.3.2 Cultivar Selection

Cultivars were chosen for this study based on a number of factors, including maturity, quality and agronomic performance, and popularity with growers. Clark, though a comparatively older cultivar (developed 1988), is still commonly grown in Indiana and is considered the “standard of earliness” for soft red (SR) wheat in Indiana. The agronomic performance of this cultivar has been well-characterized. It has been used as a parent line by many breeders for the development of current cultivars. Branson was also commonly grown in Indiana. It is a common check cultivar used in both agronomic and quality research.

The experimental lines 9346A1—2 and 07290A1-12W were in development within the wheat breeding program at Purdue University (H.W. Ohm, personal communication, 2011) and were of interest for the performance potential.

Commercial lines Pio25R26, Pio25R62, and Pio25W43 were developed and released by Pioneer HI-BRED with good agronomic performance and consistently acceptable quality. These cultivars were popular with growers in Indiana and Michigan.

Soft white (SW) wheat cultivars E5011, E5024, and E6012 were recently released primarily for use in Michigan with better agronomic and quality performance over previously grown cultivars.

3.3.3 Grain Head Sampling

Target grain moisture was 40% down to 10% (g of water per g of dry grain x 100) with a target of 5 to 6 samples taken from each cultivar within the moisture range (Table 3.1). Cultivars were monitored daily as grain moisture reached ≈40%, near physiological maturity. Approximately 150 heads were sampled randomly within the middle of each plot once target grain moisture levels were reached. Samples were harvested by hand and immediately placed in plastic bags to prevent moisture loss.

A subsample of 10 heads was threshed and weighed immediately after harvest sampling. The threshed grain was dried thoroughly at 60^{0}C and weighed to determine the gravimetric moisture content {[(fresh weight of grain - dry weight of grain) / (dry weight of grain)] x 100}. Remaining heads were weighed fresh and dried at 38^0C until reaching the target weight near 14% moisture. This temperature and target moisture level is standard when drying high-quality wheat, as this combination prevents excessive damage to the starch and grain protein (Kirleis et al., 1982). Grain head samples were removed from the dryer and weighed periodically to ensure the desired amount of moisture loss was achieved, which ranged from a few hours to nearly 24 hours. Grain head samples below 14% moisture were not dried further. Grain head samples were threshed and cleaned prior to germination testing.

3.3.4 Germination Testing

Germination testing of the wheat seed was conducted by the Indiana Crop Improvement Association. The test entailed submerging two light-weight germination towels in cold water, then draining them of all excess water. The bottom germination towel was placed on top of a sheet of waterproof paper. One hundred seeds were then placed on top of the wet towel; the top towel was then placed on top of the seeds. On the edges, 1.27 cm of the bottom and left sides of the towel were folded up; the towels were then loosely rolled up and placed in a container. This container was placed in a cold room (10°C±1°C) for 5 to7 days in order to break dormancy. Subsequent to the cold treatment, the container was placed in a germinator for seven days at 20°C (±1°C). At the end of the germination period, the towels are removed and the seedlings were counted to determine percent germination. The test was repeated four additional times per grain moisture sample.

3.3.5 Growing Degree Day Calculations

To analyze the relationship between accumulated growing degree days and grain moisture loss, daily maximum and minimum temperature data were collected from the first recorded heading date to the last day of the harvest sampling period for each growing season. Heading date was documented for each plot when at least half of the heads were emerged. Data were collected by the Indiana State Climate Office (http://iclimate.org/index.asp). We used the modified GDD formula recommended by Nielsen (2012) to determine dry-down of corn with a base temperature of 10°C:

$$\text{GDD} = [(\text{daily maximum temp.} + \text{daily minimum temp.}) \div 2] - 10$$

Adjustments were made for daily maximum and minimum temperatures. The upper temperature limit was 30°C, while the lower temperature limit was 10°C. Thus, days where the maximum temperature exceeded 30°C was calculated using the ceiling value of 30°C, and days where the minimum temperature was below 10°C was calculated using the value 10°C. Daily GDD values were calculated as described. The accumulation of GDDs for each grain moisture sample was determined by adding these daily GDDs from the respective heading to harvest dates.

3.3.6 Statistical Analyses

Grain Moisture vs. Germination

To study the effects of grain moisture on germination, five cultivars of SW wheat and five cultivars of SR wheat were analyzed (Table 3.1). Regression analyses were conducted from low to high grain moisture. However, negative slopes are discussed in the inverse (i.e., germination increased as grain moisture decreased) and positive slopes are as well (i.e., germination decreased as grain moisture decreased). Linear model regressions were run using the PROC REG of SAS version 9.3 (SAS Institute, Cary, NC). Model effects were tested for significance ($P<0.05$) using the appropriate F-test. Data could not be combined over years due to differences in climate and sampling dates for in-season data and heterogeneity of variance between years. Thus, years will be discussed separately.

Grain Moisture vs. GDD

To study the relationship between grain moisture and GDD, five cultivars of SW wheat and five cultivars of SR wheat were analyzed (Table 3.1). Linear, quadratic, and combined model regressions were run using the PROC GLM of SAS version 9.3 (SAS Institute, Cary, NC). Linear models showed the most appropriate fit to observe the change in grain moisture with GDD. Model effects were tested for significance ($P<0.05$) using the appropriate F-test. Data could not be combined over years due to differences in climate and sampling dates for in-season data and heterogeneity of variance between years. Thus, years will be discussed separately.

3.4 Results and Discussion

3.4.1 Growing Conditions

Mean monthly temperature was above normal and precipitation was below normal, during the 2011-12 growing season (Table 3.2). These conditions initiated the 2012 drought, which caused rapid grain moisture loss and early maturation of the wheat. Daily temperatures were high for most of the harvest sampling period, especially after the first five days (Fig. 3.1). Almost no precipitation was received during the 20-day sampling period, with only a trace amount of rain falling on four occasions (Figs. 3.2A, 3.2B).

Mean monthly temperatures were close to normal and precipitation was above normal during the 2012-13 growing season, especially from green-up to maturation (Table 3.2). Maximum daily temperature was higher during the first half of the sampling period of 2013 compared to 2012; whereas, the second half of 2013 was lower than 2012 (Fig. 3.1A). For the majority of the sampling period, relative humidity was higher during 2013 than 2012 (Fig. 3.1B). Accumulation and frequency of precipitation was also greater in the 2013 sampling period than 2012 (Figs. 3.2A, 3.2.B).

3.4.2 Germination

Harvest grain moisture did not affect seed germination for the 2012 growing season regardless of wheat type (Fig. 3.3). Average germination was 96% for SR wheat and 97% for SW wheat in 2012. Due to low humidity and precipitation during grain maturation, little to no PHS was observed for any of the lines including the SW wheat.

Germination scores during the 2013 growing season varied widely. Germination showed no correlation to grain moisture for SW wheat and averaged 62%. However, germination increased linearly as grain moisture decreased (Fig. 3.3) for SR wheat. The germination range of SR wheat in 2013 (17 to 95 %) was still largely below acceptable standards. Indiana Crop Improvement Association noted variable germination to be a common problem throughout Indiana and neighboring states in 2013 (personal communication, 2013).

Rainfall events and high humidity during the sampling period were likely key factors in the overall decreased germination scores in 2013. Decreased germination potential of SW wheat cultivars, in particular, was likely related to PHS, which can occur in this wheat type with frequent rainfall prior to harvest. Pre-harvest sprouting can degrade starch of seed in the grain head; thereby, reducing a major energy source for germination (Humphreys and Noll, 2002). While severe manifestations of PHS can be detected visually, alpha-amylase activity can cause damage before a visual diagnosis can confirm its presence (Humphreys and Noll, 2002). This type of damage is therefore very difficult to evaluate without laboratory testing, which was not part of this study. Soft red wheat is well characterized as being partially or completely PHS resistant, while soft white varieties are usually susceptible to PHS. Preharvest sprouting of SR varieties is possible and could have decreased the germination potential in 2013. High amounts of rainfall could have decreased stored energy reserves in the kernel, which could also decrease germination. However, SW means were overall lower than SR means. Based on the mean germination scores for the two grain types in 2013, it could be inferred from the lower germination scores in the SW wheat that PHS may have occurred to a greater extent in those cultivars.

Head scab, (*Fusarium graminearum*) was observed to a minor degree on most of the samples in 2013 but not in 2012. No relationship between head scab and heading date or harvest date was observed. Head scab can reduce germination potential even with low levels of infection (Gilbert et al., 1997). Gilbert et al. (1997) reported that germination of scab-infected seeds increased when the seed was stored at a lower, controlled temperature (5°C) compared to storage at ambient temperature. This lower temperature reduced the viability of seed-borne inoculum, causing germination to improve (Gilbert et al., 1997). In this study, seed was tested for germination only 10 days after harvest for the 2013 growing season. It was stored at room temperature (16 to 20°C) during this short period. This was in contrast to the 2012 growing season, where seed was stored for 9 months after harvest at 5°C before undergoing germination testing. These previous studies suggested that the 2013 germination scores may have improved with a longer storage period, at lower temperatures (5°C), or both.

3.4.3 Grain Moisture Dry-Down

Growing degree days (GDD) accumulated from the heading dates to harvest dates were correlated to grain moisture loss for both 2012 and 2013 harvests across both grain types. Grain moisture dry-down was combined across grain types, but could not be combined across years (Fig. 3.4). Grain moisture loss was greater in 2012 than 2013 with moisture losses of 2.1% and 1.4%, respectively, for every 10 GDDs accumulated after heading (Fig. 3.4). The regression equation revealed that 376 GDD were required to reach 20% grain moisture in 2012, and that 479 GDD were required to reach 20% grain moisture in 2013. The faster dry-down of wheat in 2012 was due to the combination of higher daily temperatures (Fig. 3.1A), lower rainfall (Fig. 3.2), and lower relative humidity (Fig. 3.1B) than 2013 during the dry-down period. Sampling began on May 31 and lasted 20 days in 2012; sampling began on June 19 and lasted 22 days in 2013.

Given the extreme climatic differences between the two years, as well as the reliability of the model across grain types, the grain dry-down rate of 1.4 to 2.1 percentage points per 10 GDDs accumulated after heading was a reasonable model to predict grain loss. Replicating this study in more average years could yield a better prediction model. It may be beneficial to factor frequency and duration of rainfall events into the model.

3.5 Conclusions

Germination of SW and SR wheat was largely unaffected by grain moisture, though germination of SR wheat increased as grain moisture decreased in 2013. This finding contradicted our hypothesis, which predicted that germination would be positively affected with higher grain moisture. The results show that harvesting wheat early, when grain moisture is high, likely imposes no penalty on germination. Thus, growers wishing to harvest seed wheat at high grain moisture may be encouraged to do so, as early harvest will not likely affect the quality of their product.

Grain moisture correlated strongly with accumulated GDDs for both years and wheat types, showing decreasing moisture as GDD accumulated. The difference between years was likely caused by the extreme differences in weather, especially in humidity and precipitation received during the periods from heading to harvest. The simple, linear models in two extreme weather years provides good tool for growers to predict dry down of wheat. With more study, it is likely that a useful, reliable prediction model for grain moisture loss versus GDD could be developed in wheat.

3.6 References

Bergstrom, G.C. (1993). Scab (Fusarium Head Blight). Pages 83-93. *Seed-borne Diseases and Seed Health Testing of Wheat,* ed. S.B. Mathur and B.M. Cunfer. Danish Government Institute of Seed Pathology for Developing Countries. Copenhagen. 168 pp.

Cavalieri, A.J., and O.S. Smith. (1985). Grain Filling and Field Drying of a Set of Maize Hybrids Released From 1930 to 1982. Crop Science 25(5):856-860.

Food and Agriculture Organization. Food Outlook, May, 2008. Available via <http://www.foa.org/docrep/010/ai466e/ai466e03.htm>. Accessed 11 November 2011.

Gilbert, J., A. Tekauz, and S.M. Woods. (1997). Effect of Storage on Viability of Fusarium Head Blight-Affected Spring Wheat Seed. Plant Disease: 81(2): 159-162.

Groos, C., G. Gay, M.R. Perretant, L. Gervais, M. Bernard, F. Dedryver, and G. Charmet. (2002). Study of the relationship between pre-harvest sprouting and grain color by quantitative trait loci analysis in a white x red grain bread-wheat cross. Theoretical and Applied Genetics 104:39-47.

Humphreys, D.G. and J. Noll. (2002). Methods for characterization of preharvest sprouting resistance in a wheat breeding program. Euphytica 126:61-65.

Kidd, F. and C. West. (1919). Physiological pre-determination: The influence of the physiological condition of the seed upon the course of subsequent growth and upon the yield. III. Annals of Applied Biology 5:157-170.

Lloyd, B.J., T.J. Siebenmorgen, R.K. Bacon, and E. Vorries. (1999). Harvest Date and Conditioned Moisure Content Effects on Test Weight of Soft Red Winter Wheat. Applied Engineering in Agriculture 15(5):525-534.

McNeill, S., D. Overhults, and M. Montross. (2008). Harvesting, Drying, and Storing Wheat. Univ. Kentucky. Accessed online. <http://www2.ca.uky.edu/agc/pubs/id/id125/10.pdf>.

Nielsen, R.L. (2012). Heat Unit Concepts Related to Corn Development. Purdue Univ. Dept. of Agronomy. Accessed online. <http://www.agry.purdue.edu/ext/corn/news/timeless/heatunits.html>.

Scott, G.E., E.G. Heyne, and K.F. Finney. (1957). Development of the Hard Red Winter Wheat Kernel in Relation to Yield, Test Weight, Kernel Weight, Moisture Content, and Milling and Baking Quality. Agronomy Journal 49(9):509-513.

Table 3.1.Cultivars and respective grain color, grain hardness, release year, heading date, and sampling date range for the 2011-12 and 2012-13 growing seasons. Cultivars were sampled as grain moisture decreased from approximately 40 to 10% at West Lafayette, Indiana.

			2011-12 Season		**2012-13 Season**	
Cultivar	**Grain Type**	**Release Year**	**Heading Date**	**Sampling Range**	**Heading Date**	**Sampling Range**
Branson	soft red	2005	4/24	5/31 to 6/11	5/15	6/19 to 7/3
Clark	soft red	1988	4/24	5/31 to 6/11	5/15	6/19 to 7/3
9346A1--2	soft red	nr†	4/24	5/31 to 6/12	5/16	6/20 to 7/3
Pio25R26	soft red	1996	4/29	6/7 to 6/14	5/19	6/27 to 7/10
Pio25R62	soft red	2007	4/26	6/7 to 6/11	5/17	6/21 to 7/3
07290A1-12W	soft white	nr†	4/25	6/5 to 6/13	5/16	6/20 to 7/3
Pio25W43	soft white	2007	4/26	6/5 to 6/12	5/17	6/21 to 7/3
E6012	soft white	2011	4/27	6/6 to 6/12	5/18	6/24 to 7/3
E5011	soft white	2010	5/3	6/12 to 6/19	5/20	6/27 to 7/10
E5024	soft white	2011	5/3	6/12 to 6/19	5/20	6/27 to 7/10

†nr= not released

Table 3.2. Mean monthly temperature and precipitation during the 2011-12 and 2012-13 growing seasons (October-July), with deviations from the 30-yr normal (1981-2010). No data is shown for July of the 2011-2012 season, as harvest was completed in June. Data were collected at West Lafayette, Indiana.

	2011-2012 Season				**2012-2013 Season**			
Month	**Mean Air Temp.†**	**Dev.‡**	**Precip.§**	**Dev.**	**Mean Air Temp.**	**Dev.**	**Precip.**	**Dev.**
	---------°C---------		------mm------		----------°C---------		------mm------	
October	12.5	0.8	26.1	-51.4	10.8	-0.9	83.3	5.8
November	8.4	3.0	68.6	-13.7	4.8	-0.6	14.0	-68.3
December	2.1	3.9	118.2	56.0	3.9	5.7	80.7	18.5
January	-1.0	3.1	88.0	39.2	-1.9	2.2	111.5	62.7
February	1.0	2.8	26.1	-21.1	-1.8	0.0	61.4	14.2
March	13.2	9.3	49.0	-17.3	0.7	-3.2	23.7	-42.6
April	11.2	0.7	27.0	-63.9	9.6	-0.9	160.5	69.6
May	19.6	3.2	69.8	-51.1	18.1	1.7	77.2	-43.7
June	22.2	0.6	19.6	-84.3	21.8	0.2	105.9	2.0
July	-----	---	-----	---	21.6	-1.4	68.3	-38.4
Total			492.4	-207.6			786.5	-20.2

†Temp. = Temperature.

‡Dev. = Deviation from 30-yr normal (1981-2010) for temperature or precipitation based on preceding column.

§Precip. = Precipitation.

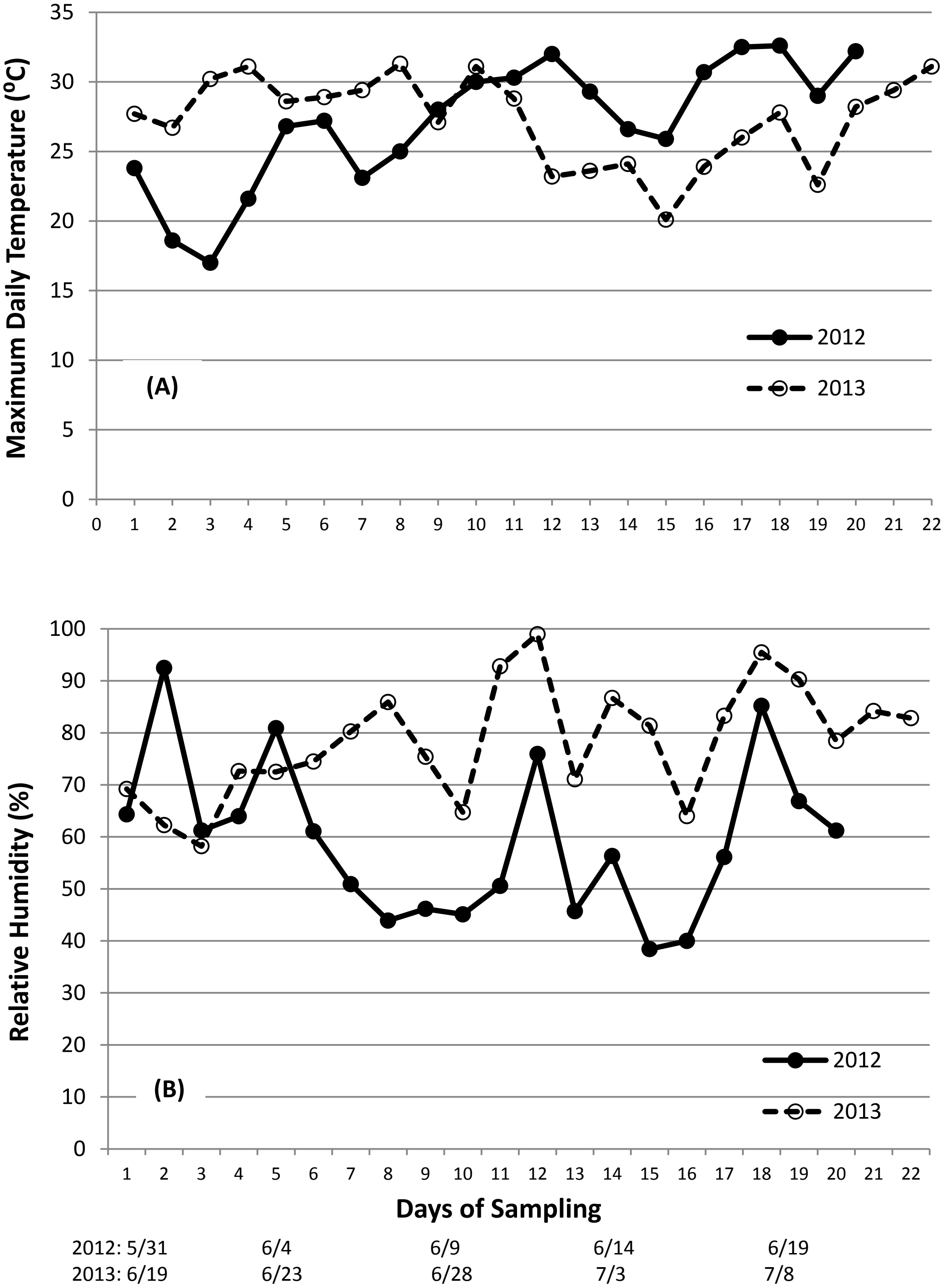

Figure 3.1. (A) Maximum daily temperature and (B) average relative humidity during the harvest sampling period, which lasted 20 days in 2012 (May 31 to June 19) and 22 days in 2013 (June 19 to July 10) at West Lafayette, Indiana.

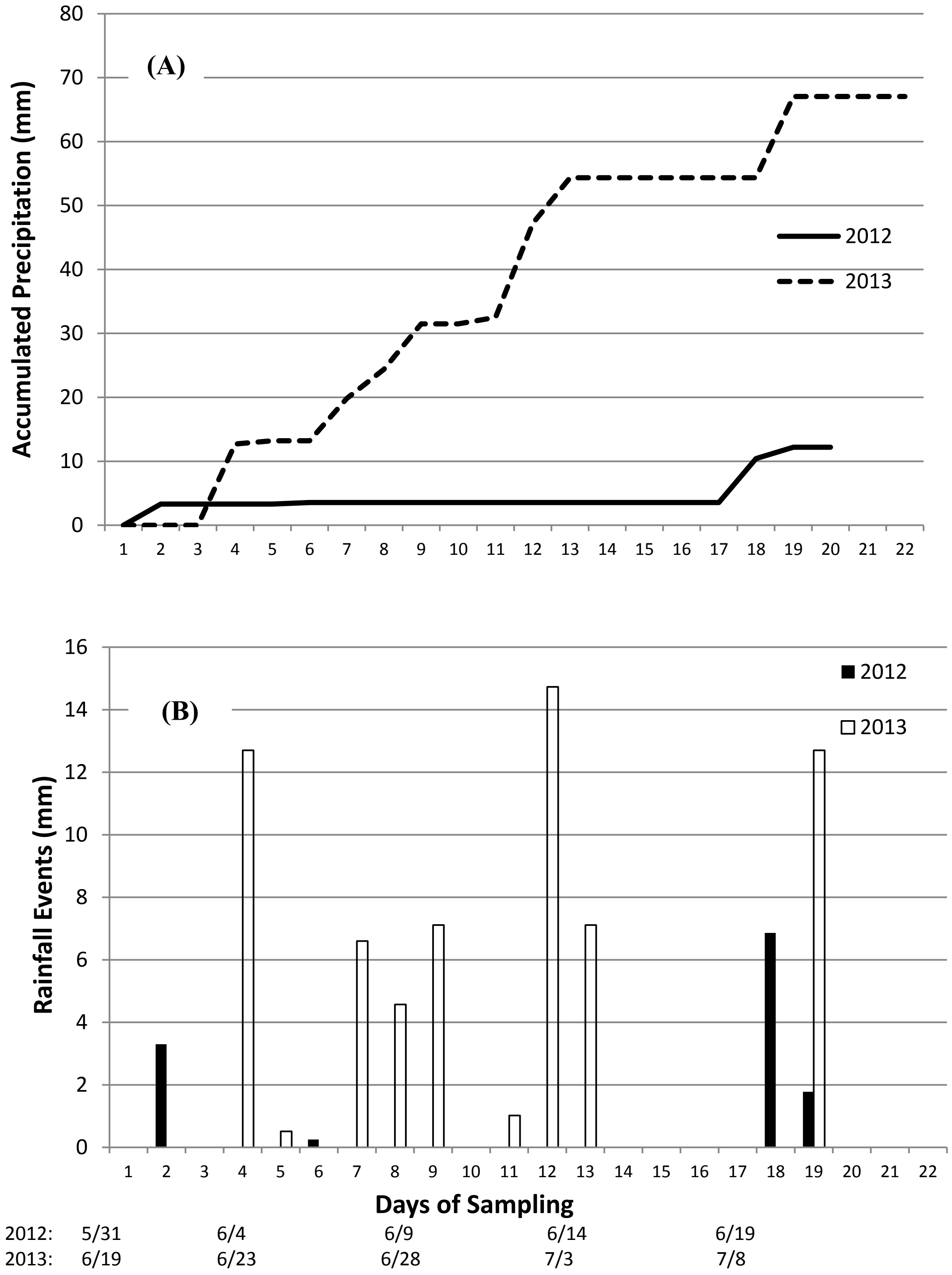

Figure 3.2. (A) Accumulated precipitation and (B) rainfall events during the harvest sampling period, which lasted 20 days in 2012 (May 31 to June 19) and 22 days in 2013 (June 19 to July 10) at West Lafayette, Indiana.

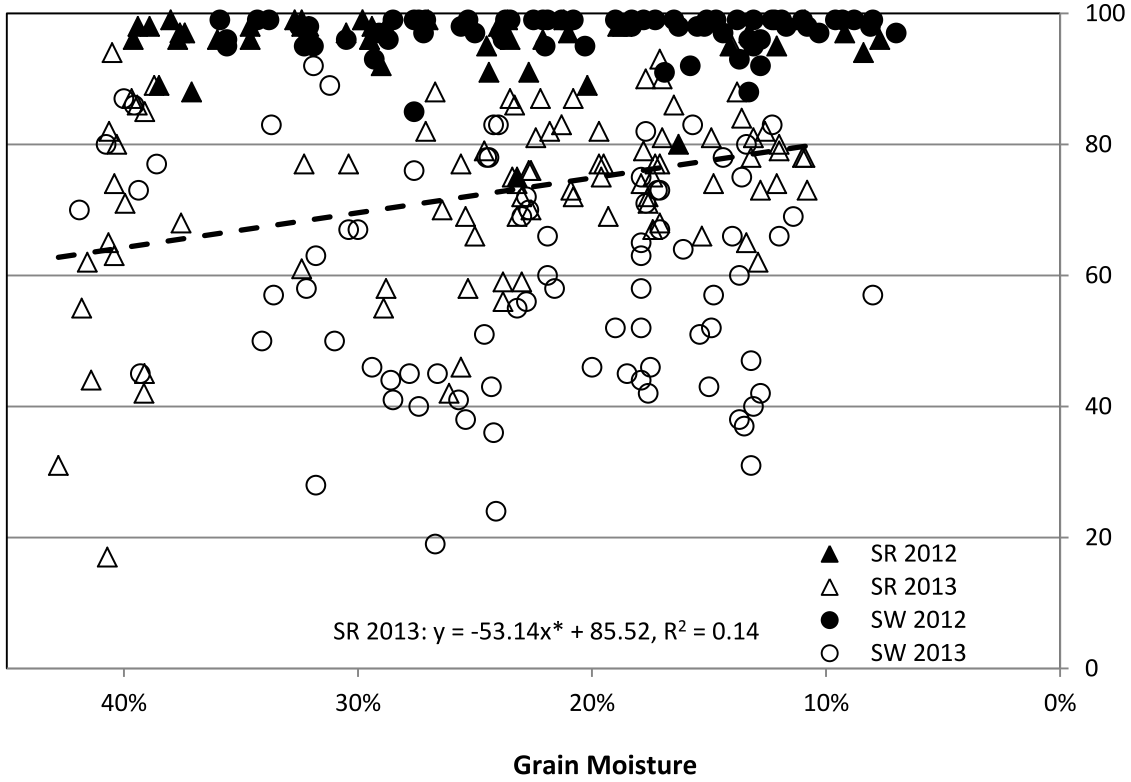

Figure 3.3. Effects of harvest grain moisture on seed germination. Ten cultivars were sampled as grain moisture decreased from approximately 40 to 10% at West Lafayette, Indiana, in 2012 and 2013 and a subsequent germination test was performed on the harvested grain; *, **, and *** represent significance at P=0.05, 0.01, and 0.001; respectively.

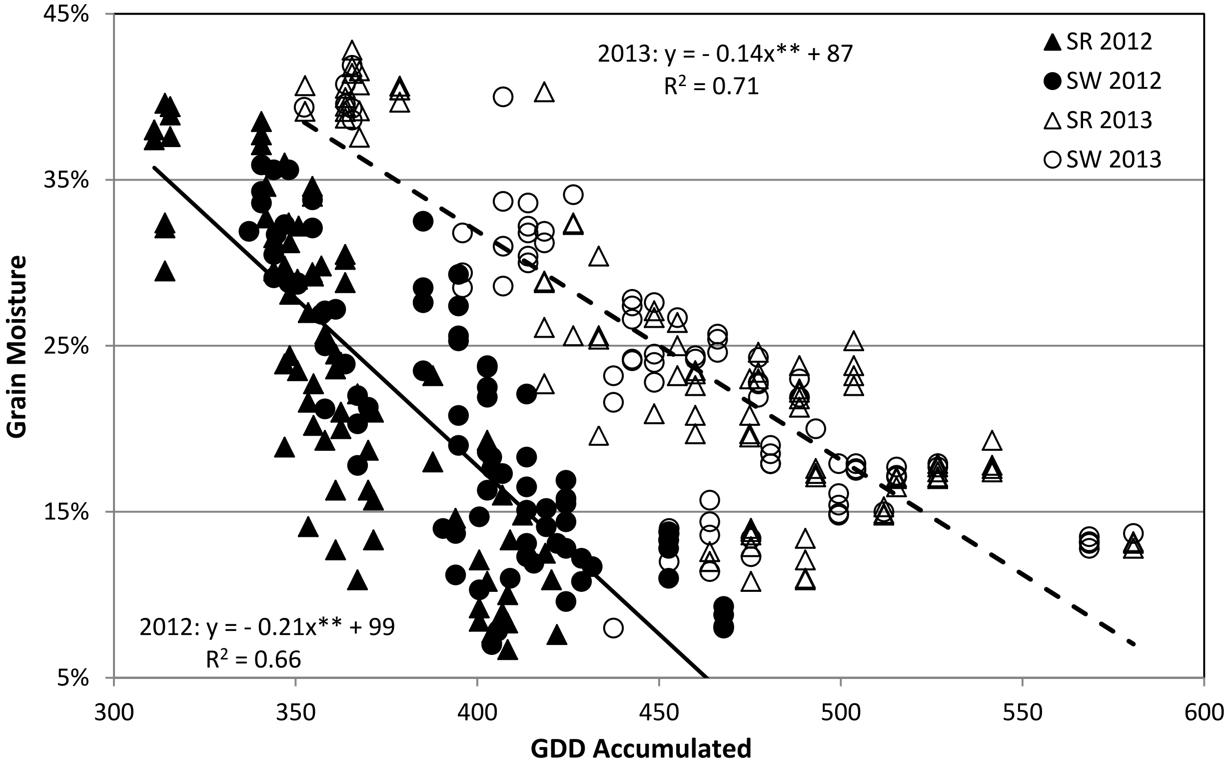

Figure 3.4. Linear relationship of grain moisture loss to accumulated growing degree days (GDD) from heading to harvest date. Ten cultivars were sampled as grain moisture decreased from approximately 40 to 10% at West Lafayette, Indiana, in 2012 and 2013; *, **, and *** represent significance at P=0.05, 0.01, and 0.001; respectively.

APPENDIX

Table A.1. Eliminated cultivars and respective grain color, grain hardness, release year, heading date, and sampling date range for the 2011-12 and 2012-13 growing seasons. Cultivars were sampled as grain moisture decreased from approximately 40 to 10% at West Lafayette, Indiana.

			2011-12 Season		2012-13 Season	
Cultivar	**Grain Type**	**Release Year**	**Heading Date**	**Sampling Range**	**Heading Date**	**Sampling Range**
NY91017-8080‡	soft white	2005	5/1	6/12 to 6/15	5/20	6/27 to 7/10
06397C1-1-2W§	soft white	nr†	4/22	5/31 to 6/11	5/15	6/19 to 7/3
Wesley¶	hard red	1998	5/6	6/12 to 6/19	5/20	6/27 to 7/10
Danby¶	hard white	2006	4/28	6/7 to 6/14	5/18	6/24 to 7/10

†nr= not released

‡Excluded from analyses due to excessive amount of off-type plants in plots

§Excluded from analyses due to frost damage to grain heads

¶Excluded from analyses due to hard grain type and quality differences

Table A.2. Average yields of wheat cultivars by year and location. Cultivars were planted in three replicates at West Lafayette, Indiana in 2012 and 2013, and at Wanatah, Indiana, in 2013. Yield was measured in kilograms (kg) per hectare (ha).

		West Lafayette		**Wanatah**
Cultivar	**Grain Type**	**2012 Yield**	**2013 Yield**	**2013 Yield**
06397C1-1-2W	soft white	1437	2756	3667
07290A1-12W	soft white	3409	4138	4747
9346A1—2	soft red	2642	4092	3958
Branson	soft red	4168	5092	5042
Clark	soft red	2651	3565	3201
Danby	hard white	3808	3079	3231
E5011	soft white	4397	3987	4744
E5024	soft white	4808	4074	4484
E6012	soft white	4566	4249	4493
NY91017-8080	soft white	3034	3865	3852
Pio25R26	soft red	4781	3918	5171
Pio25R62	soft red	5455	5075	5342
Pio25W43	soft white	4432	4787	4786
Wesley	hard red	3773	3487	3990

Table A.3. Grain type, and release year, and parentage of wheat cultivars. Cultivars were planted in three replicates at West Lafayette, Indiana in 2012 and 2013, and at Wanatah, Indiana, in 2013.

Cultivar	Grain Type	Release Year	Parentage
06397C1-1-2W	soft white	nr†	INW0411/KS24-2-2(275-4)
07290A1-12W	soft white	nr†	992060G1/92829A1
9346A1—2	soft red	nr†	831800A1-7-2-5-2/861A1-8-x-38
Branson	soft red	2005	(891-4584-A)Pike/FL-302
Clark	soft red	1988	67137B5-16/Sullivan
Danby	hard white	2006	Trego/KS84063-9-39-3-8W
E5011	soft white	2010	Caledonia/Richland
E5024	soft white	2011	MSU D6234/Pio25W33
E6012	soft white	2011	Caledonia/Pio25W33
NY91017-8080	soft white	2005	U1166/Harus
Pio25R26	soft red	1996	S76sib/5517A5-5-IP-3
Pio25R62	soft red	2007	WBN0686C/WBJ0249B1
Pio25W43	soft white	2007	Pio25W33/WBL0305A1
Wesley	hard red	1998	KS831936-3/NE86501

†nr= not released